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WATER RESOURCES ACTIVITIES IN THE UNITED STATES. THE IMPACT OF NEW TECHNIQUES ON INTEGRATED MULTIPLE-PURPOSE WATER DEVELOPMENT

Edward A. Ackerman

Select Committee on National Water Resources,
U. S. Senate

March 1960

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THE IMPACT OF NEW TECHNIQUES ON INTEGRATED MULTIPLE-PURPOSE WATER DEVELOPMENT

SELECT COMMITTEE ON NATIONAL WATER RESOURCES
UNITED STATES SENATE

PURSUANT TO

S. Res. 48

EIGHTY-SIXTH CONGRESS

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STATEMENT BY THE CHAIRMAN

March 8, 1960.

To the Members of the Senate Select Committee on National Water Resources:

Under the provisions of Senate Resolution 48, our committee is directed to study the extent and character of water resources activities, both governmental and nongovernmental, that can be expected to be required to provide the quantity and quality of water for use by our population, agriculture, and industry between now and 1980, along with suitable provision for related values. Among other matters, the committee is directed to consider the character and extent of water resource projects that will be needed and the character of legislation that may encourage the adoption of new technical and improved processes for increasing the usefulness of available water resources.

It has long been evident that one of our primary needs is for adequate consideration to be given all purposes in the development of water resources projects. This concept goes under the term of "comprehensive, multiple-purpose development" and has been urged as an objective of river basin development since Theodore Roosevelt's Inland Waterways Commission of 1907. It is evident that as demands for water grow it will be more and more necessary to consider multiple uses in all water resources activities, in order that all purposes can be served. As new techniques for making better use of water become necessary and are developed, these will have significant effects on our pattern of river basin development, as it becomes more and more necessary, if not mandatory, for us to put all of our water resources to the best possible use.

In order to provide background information on the relationship of new technical methods to multiple-purpose development, this committee on August 18, 1959, approved a contract with a group directed by Dr. Edward A. Ackerman, a leading water resources expert, for the preparation of a report which would explore this subject and present full information concerning it for the committee. The contract was approved by the Rules Committee as of August 18, 1959. Under it, a report was called for containing a summary of new technical developments, including but not limited to weather modification, evaporation and evapo-transpiration reduction, desalination of saline and brackish waters, seepage control, waste water salvage, and the application of nuclear energy, as these techniques are likely to affect the planning of river basin development and future river management in the United States. The contract called for an evaluation of possible effects of such techniques on the manner of comprehensive river basin planning and on multiple-purpose river management, and for suggestions as to actions that might be taken to hasten or otherwise aid future application of beneficial new technology to comprehensive river development and water conservation.

The excellent report furnished under the contract presents ~~an interesting~~ and thought-provoking survey of comprehensive, multiple-purpose water development as it is expected to be needed in the future. The report discusses the future environment in which water development is expected to be undertaken, the general relation of technological change to efficient water development and water management, and goes into the general and also some of the more specific problems on which attention will necessarily be focused in our future river basin development. It predicts that increasing water problems in virtually every part of the United States will require development of water resources on a scale and at a rate heretofore not experienced. It points out that extensive areas will have to go beyond present methods of development if requirements are to be met. In these areas, it projects the need for more advanced methods to achieve fullest possible use of surface waters, plus all that scientific research can make available from underground sources and the atmosphere. It advises taking the long-term view in considering action to meet the Nation's growing water problems because any major program decision now will set the form of development for decades to come.

Based on these findings the report advances eight suggestions as to actions for encouraging future efficiency in water resources development by improving the Nation's water resources policies. The report suggests that, should they be deemed worthy by the Congress, four of these suggestions could be readily implemented without any change in our existing administrative and legal structure. These are as follow:

(1) Provide for creation or completion of basinwide water regulation systems as a primary objective of Federal activity on all streams where appropriate.

(2) Modernize and expand our basic data collection to adequately serve requirements of comprehensive development.

(3) Protect dam, reservoir, and other sites needed for comprehensive development from future encumbrance for other less essential purposes, and

(4) Recognize the future dominant importance to the Nation of meeting urban and industrial water requirements.

The other four suggestions, which it is suggested would require careful and specialized study, and evolution of policy over a period of time in the light of such study, should the Congress be inclined to favor them, are:

(5) Establishment of truly comprehensive development as the procedural pattern for all future Federal action in the water resources field,

(6) Simplification of Federal program concerned with direct water use,

(7) Development of strategy for growth and application of technical improvements in water resources development, and

(8) More adequate recognition of the opportunities for economy in the development of large-scale projects, particularly in the field of electric power.

The report suggests various specific ways in which the first four suggestions might be made effective, and by which appropriate deliberative study could be given the others as a means of determining whether and how they should be implemented.

This report will be of value to you, to other Members of the Senate, and to all who are interested in finding the solution to the Nation's water resources problems. Accordingly, I am having it printed as one of our committee prints on water resources activities which are being considered by the committee. It must be recognized that, as in the case of the previous reports, the views and policy recommendations contained in this report are those of its authors, and have not been adopted by the committee or the committee staff.

Rob't S. Kerr,
Chairman, Select Committee
on National Water Resources.

PREFACE

An engineer engaged in international practice recently said—

> When it is remembered that the water industry overshadows all other industries in the volume of the raw materials it handles, that investments in this industry now amount to the equivalent of $200,000 to $300,000 million and are expanding at the rate of $10,000 million a year, it is difficult to understand why modernization is so slow in coming.[1]

This report, prepared at the request of the U.S. Senate Select Committee on National Water Resources, examines some aspects of modernization which may be of interest in the formation of public policy for this basic and extremely complex aspect of our national life. It examines reasons why efficiency may be needed in public participation in and leadership for water development. An effort is made to suggest what dynamic management of water resources may be, and to outline the opportunities and problems associated with known new techniques and the further application of research and experiment. The objective is achievement of true comprehensive development of U.S. water resources. The ratio of population to our water resources will increase sharply within this century, bringing acute pressure on some regional supplies. Although allocation and even rationing cannot be avoided in some situations, it is the business of technology and management to keep the need for these measures as near a minimum as possible. The suggestions set down herein are made in that spirit.

Warm thanks are due to those who made the appearance of the report possible in its present form. Dr. Donald Patton assisted in a very able manner with research and data compilation throughout the preparation of the report. Appendix 10 and the model of water transportation (table H, appendix 11) were prepared by Dr. Patton. The report has profited much from the critical review given the mimeographed edition by Dr. George O. G. Löf, of Denver, Colo., Mr. Frank L. Weaver, Washington, D.C., Mr. Maynard M. Hufschmidt, of Harvard University, Prof. Gilbert F. White, of the University of Chicago, Dr. Alfred Loehnberg of Mexico, D. F. Mexico, and Dr. Patton. Dr. Löf also assisted in the preparation of data on western water use.

The permission of Arthur Maass and Maynard M. Hufschmidt to reprint excerpts from their forthcoming published account of the "Harvard Program of Research in Water Resources Development" as appendix 4, and the time they gave in consultation on the preparation of the excerpts are much appreciated. The same is true for the careful attention and initiative of Franklin S. Pollak of the Bureau of State and Community Service, University of Colorado, who obtained the university's permission to publish the excerpts in advance of the book which will contain the account of the Harvard program. The cooperation of the city of Phoenix, Ariz., and the city of Denver, Colo., in preparing data on their water use is acknowledged. The assistance of Roy Oltman of the U.S. Geological Survey helped much in the preparation of appendix 11. Special thanks are due to Mrs. Ailene J. Bauer of the Carnegie Institution of Washington for her advice and supervision of manuscript preparation. The hours patiently endured by Barbara Kreimer and Marjorie Walburn of the Institution in typing and other tasks of manuscript preparation also are gratefully acknowledged.

Responsibility for all statements made and conclusions reached in the report rests entirely with the author.

Unless otherwise noted in the text, the discussion and data presented are limited to the 48 States comprising the middle latitude territory of the United States.

EDWARD A. ACKERMAN.

WASHINGTON, D.C.
Revised March 10, 1960.

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[1] Alfred Loehnberg, "Water and Economic Development," "Impact of Science on Society," vol. IX (1958), pp. 43-44.

CONTENTS

Page
Statement by the chairman III
Preface V
Summary 1
I. Present design of integrated multiple-purpose development 4
II. The future technico-economic environment in which water development will be undertaken 7
    Population 8
    The location of manufacturing industries 9
    The nature and location of agricultural production 9
    Other aspects of land use influencing water requirements 11
    The general rate of technical progress in the Nation 11
    Land-use planning 12
    Summation of reasons why efficiency will be sought in water development 13
III. The general relation of technologic change to efficiency and water development and water management 13
    Techniques with potentials for effecting integrated multiple-purpose development 14
        Planning, design, and operation of systems of multiple-purpose works 14
        Prognostic hydrology 18
        New techniques of physical design 19
    Exploration for, discovery, and exploitation of new supplies 19
    Measures for conservation and reduction of demand 22
        Recycling 22
        Vegetational management for water yield 22
        Evaporation suppression 23
        Location of demand by planning land use 24
    Treatment and use of waters having substandard quality 25
        The question of economical means of treatment 26
        Problems presented by new types of waste 31
        Recognition of treatment techniques as a part of water development 31
        Use priorities corresponding to water quality 31
IV. The organization of development 32
V. Some general problems of future development 33
    Recognition of new types of regional requirements 33
    Scale of development and program design 35
        Full use of scale economies in integrated development 35
        Coordination of tributary and main-stem development 35
        Achievement of scale economies in water related services 37
    The weighting of future obsolescence in program design and financing 38
    Coordination of Federal operations with those of other public or private agencies having impinging areas of interest 39
VI. Future comprehensive development and related special problems 40
    The related problems 42
        Preservation of reservoir and damsites 42
        Fundamental research in related scientific disciplines 43
        Collection and interpretation of basic data 44
        Experiment with innovations in development procedure 44
        Evaluating progress and reviewing experience 45
        The choice of Federal functions 45

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Page
VII. Suggestions for a policy encouraging future development efficiency ---- 46
  1. Establish a national procedure of comprehensive development ---- 47
  2. Complete basic water control systems ---- 47
  3. Simplify the Federal program concerned with direct use ---- 48
  4. Develop strategy for the growth and application of technical improvement ---- 49
  5. Modernize and expand basic data collection and interpretation ---- 49
  6. Protect essential storage and damsites ---- 49
  7. Recognize the influence of future urban requirements ---- 49
  8. Recognize the opportunity for related economies of scale ---- 49
  Policy implementation ---- 49
  Policy elements which could be implemented readily ---- 50
  Policy elements best implemented deliberately ---- 50
    Value of the regional water development study commissions ---- 51
  Possible national benefits from some policy changes ---- 51

LIST OF FIGURES

Figure 1. Regional comparisons of land area, runoff, and possible population totals, year 2000. Land-area comparisons are for middle latitude United States only ---- 7
Figure 2. Two major U.S. areas with numerous urban settlements and high percentages of employment in pursuits associated with urban centers; (1) generalized boundaries of 1960 areas; (2) possible future extensions of the northeastern-midwestern area ---- 8
Figure 3. The national system of Interstate and Defense highways. (U.S. Department of Commerce, Bureau of Public Roads, September 1959) ---- 10
Figure 4. Percentage adequacy of ground-water information, United States (from Langbein and Hoyt, "Water Facts for the Nation's Future," pp. 26–27) ---- 20
Figure 5. Great Plains drought periods (from "A Report on Drought in the Great Plains and Southwest," prepared under the direction of the Special Assistant to the President for Public Works Planning, October 1958) ---- 27
Figure 6. Saline surface and ground water in the United States (from Ackerman and Löf, "Technology in American Water Development," p. 346) ---- 28
Figure 7. Regions of potential demand for demineralized sea water for irrigation (from Ackerman and Löf, op. cit., p. 344) ---- 29
Figure 8. The Mississippi River Basin, including its principal tributary basins ---- 36
Figure 9. New England, Mid-Atlantic States and California Electric Power Service Areas (from Ackerman and Löf, pocket map) ---- Faces 37
Figure 10. Water resource regions corresponding to the four sectional groupings of States ---- 42

LIST OF TABLES

Table 1. U.S. soil conservation districts, 1938–59 ---- 12
Table 2. Planning agencies in the United States, 1945–58 ---- 12
Table 3. American Institute of Planners membership, 1945–59 ---- 12
Table 4. Some techniques related to future efficiency of U.S. water resource development ---- 15
Table 5. Estimate of potential precipitation increases by artificial cloud seeding in Western States ---- 21
Table 6. Regions of potential demand for demineralized sea water for irrigation ---- 30
Table 7. Thermal electric stations in New England and California by size groups ---- 38
Table 8. Applicability of some techniques of comprehensive development, by river basin, 1960–2000 ---- 41

PHOTOGRAPHS

Plate I:
  (a) Trenton Dam, Nebr ---- 53
  (b) Anderson Ranch Dam, Idaho ---- 53
  (c) Earthmoving equipment at Trenton Dam ---- 53
Plate II:
  (a) Hungry Horse Dam, Mont., under construction ---- 54
  (b) Soap Lake siphon, Columbia Basin project, Washington ---- 54
Plate III:
  (a) Clifty Creek plant of Indiana-Kentucky Electric Corp ---- 55
  (b) Kingston steamplant of the Tennessee Valley Authority ---- 55
Plate IV:
  (a) 450,000-kilowatt turbine-generator of the Indiana & Michigan Electric Co ---- 56
  (b) Morro Bay plant of the Pacific Gas & Electric Co., California ---- 56

APPENDIXES

Page
Appendix 1. Future urban growth in the United States 59
Appendix 2. Water resource planning and development in agriculture 62
Appendix 3. Brief description of systems analysis methods 63
Appendix 4. Report on the Harvard program of research in water resources development (excerpts) 64
Appendix 5. Synthetic hydrology and probability analysis 78
Appendix 6. Reasons for an economic analysis of weather modification 78
Appendix 7. Summary evaluation of known techniques for discovery and appraisal of ground-water deposits 80
Appendix 8. Water budgeting and irrigation 81
Appendix 9. Thermal-electric generation; correlation of efficiency with size of unit and size of plant 86
Appendix 10. The use of nuclear explosives in water resource development, by Donald Patton 87
Appendix 11. The applicability of comprehensive development to the water problems of the nine Southwestern States, 1960–2000 89

FIGURES IN APPENDIXES

Figure A. Cost—capacity function, storage dam 66
Figure B. Output—capacity function, storage dam 67
Figure C. Cost—output function, storage dam 67
Figure D. Gross benefit-output curve 68
Figure E. Two reservoir-single purpose system, iso-cost and iso-output functions 69
Figure F. Expected net benefit-scale of development function with confidence limits 71
Figure G. Prototype river basin system 72
Figure H. Map of Simple Valley 76
Figure I. Annual march of precipitation and potential evapotranspiration at Seabrook, N.J. (from Ackerman and Löf, op. cit., p. 446) 83
Figure J. Typical irrigation schedule in humid Eastern States (from Ackerman and Löf, op. cit., p. 449) 85
Figure K. Total production expenses (excluding fuel) of 100- and 200-megawatt thermal-electric generating units compared to plant size, based on 8,000 hours' use, 1957 (Tennessee Valley Authority, Office of Power, 1959) 87
Figure L. Per capita water consumption from municipal systems, Denver, Colo., and Phoenix, Ariz. Sources: Statistical data from Phoenix Department of Water and Sewers, and city of Denver 91
Figure M. Hardness of surface and ground waters in the United States (from Ackerman and Löf, op. cit., p. 216) 93
Figure N. Some functions in the implementation of comprehensive development, as related to each other and to legislation 96

TABLES IN APPENDIXES

Table A. Objective functions 64
Table B. System units and outputs 70
Table C. Four estimates of stream runoff in Texas 89
Table D. Some basic data for evaluating water requirements in the Southwestern States, year 2000 90
Table E. Average annual runoff during driest 6-year period and driest 10-year period and runoff of driest single year between 1921 and 1959, as a percentage of normal runoff, nine Southwestern States 90
Table F. Estimated runoff in Texas, 1946–57, and cumulative departure of precipitation 92
Table G. Usable reservoir storage capacity, nine Southwestern States, January 1, 1954 92
Table H. A model of long-distance water transportation by conduit in Western United States 94

THE IMPACT OF NEW TECHNIQUES ON INTEGRATED MULTIPLE-PURPOSE WATER DEVELOPMENT

(By Edward A. Ackerman)

SUMMARY

Water development is the matching of water supply to existing or potential demand for water and water services. The outstanding instruments to promote efficiency in development have been the techniques of integrated multiple-purpose design and management. The report commences with these assumptions: (*a*) Improvement in efficiency to the extent required by long-term needs will be a basic purpose in U.S. water development; and (*b*) multiple-purpose water regulation and integrated system operation of facilities for regulation are essential steps toward efficiency. The purpose of the report is an evaluation of the effects of future technology on these steps, and comment upon resulting public policy problems.

Efficiency will be sought in future development because of the anticipated large total growth of population and economic requirements, a change to a heavily urban population concentrated in dense settlements of vast extent, the dispersal of industry and residential settlement, and changes in occupational structure creating needs for service industry employment. These pressures will be supplemented by locally organized land use planning, and the astonishing acceleration of general technical progress to be expected in the Nation.

New techniques

As new requirements arise they may be met for a time everywhere by extensions of existing practice; in some areas existing practice may be adequate indefinitely. However, the huge problems anticipated in some parts of the country suggest advantages in methodically evaluating possible additions to, or modification of existing practice. These additions or modifications are to be sought in:

(*a*) *Improved planning, design, construction, and operation of systems of multiple-purpose works.*—The techniques which may be examined as offering some potentially useful modification include operations analysis, construction of consumption models, prognostic hydrology, materials economizing design, construction methods and the use of nuclear explosives.

(*b*) *Exploration for, discovery, and exploitation of, new water supplies.*—The techniques worthy of consideration here are weather modification, geophysical and other exploration of aquifers, and engineering experiment with ground water lifting.

(*c*) *Measures for conservation and reduction of demand.*—Potentially useful techniques under this heading are recycling, water-conserving agronomy, forest and range management for water yield, evaporation suppression, and planned location of demand by a publicly controlled land use.

(*d*) *Treatment and use of waters having substandard quality.*—Among these techniques are treatment of organic wastes, treatment of nonradioactive chemical wastes, treatment of radioactive wastes, desalting, sediment control, and water use priorities.

General problems facing development

The applicability of any one of these techniques profitably may be examined in the light of anticipated general problems facing future water development, where efficiency is sought. Several such problems may be identified among the three major steps of development—planning, realization of development, and operational management. Among the problems mentioned in the report are:

(*a*) *The recognition of new types of regional requirements.*—The traditional and simple distinction between east and west no longer will suffice as a regional basis for policy formation. It is suggested that planning may be more efficiently and more satisfactorily undertaken if the existence of four distinct regions is recognized: The southwestern nine States, the northwestern eight States, the northeastern-midwestern urban zone, and the southeast. The southwestern and northeastern-midwestern regions are the areas within which the heaviest pressure upon water resources will be reached in the future. Accordingly, they will offer the most stringent tests of policy, although this certainly does not mean the absence of development problems elsewhere in the country.

(*b*) *Scale of development and program design.*—There may be opportunities for more complete use of economies of scale in integrated basin development. For example, the question of planning the entire Mississippi system as a unit still may be an open one. Problems of coordinating tributary and main-stem development also exist.

(*c*) *Achievement of scale economies in water-related services.*—This is principally a question of economies of scale in the generation and distribution of electricity. Full use of these economies has not been achieved in some populous parts of the country. Although most future additions to electricity generation will be fuel powered, hydro generation still will be important enough to warrant considering size of distribution systems in connection with water policy.

(*d*) *The weighting of future obsolescence in program design and financing.*—The major works for storage and detention have service lives which can be determined, and are sufficiently long not to be of concern in the period studied. However, the accelerating rate of scientific and technological effort bring higher and higher probabilities of influential changes in costs of producing energy, manner of agricultural production, costs of transportation, and other facilities related to the final use of water. Assumption of a service life of more than a few decades therefore seems unrealistic for many facilities directly connected with final use of water. This is significant in the calculation of rates of return from vendible services and the confidence to be placed in exact schedules of repayment.

(*e*) *Coordination of Federal operations with those of other public or private agencies having impinging areas of interest.*—Coordination should be undertaken in a manner which will assure that benefits from the economies of scale realizable through basinwide development or large-scale organization of distribution facilities will be available in all parts of the country where they are reasonably attainable. In addition, the Federal Government should be certain that large-scale developments, like some ground water "mining" on the Great Plains, is an efficient pattern for the long run, considering both private investment and probable needed later public investment.

Comprehensive development

These general problems clearly indicate a situation some time within this century in which water requirements will cause the Nation to go beyond traditional approaches to water development. For this new type of approach the term "comprehensive development" is suggested. By it we mean the application of integrated multiple-purpose design, planning and management which include joint consideration of ground and surface waters, conservational and other measures for "engineering" of demand, and the treatment and management of waters having substandard quality. Consideration of every appropriate technique would be a routine part of planning for development. It is the thesis of the report that comprehensive development will be achieved by the United States as standard practice at some time during the remainder of this century. It is also believed that its application, understood in these terms, will be highly desirable at an early date in the nine Southwestern States. To a degree it also will be needed in the northeastern-midwestern urban zone. A methodical evaluation shows that nearly all of the techniques here described under comprehensive development are applicable within the southwestern river basins.

If comprehensive development is accepted as desirable future practice, several further problems bear mention. The first is the protection of reservoir and dam sites from encumbrance by land uses which forestall future efficient river basin development. A second is the need to review and plan a strategy for fundamental research in scientific disciplines related to water development. In spite of the huge national effort going into science at the present time, some program expansion in fields like atmospheric physics, hydrology, and plant genetics might prove potentially valuable for later water development. A third is the need for improvement in basic data coverage. An adequate basic data policy should prepare the ground for full realization of the economies of scale through integrated multiple-purpose regulation; it should permit the drafting of efficient long-range plans of ground water exploitation which is integrated with surface water use; it should provide projections of precipitation cycles; it should provide for foresighted monitoring of water quality; it should provide inventories of unused supplies; and it should anticipate the application of comprehensive development.

A fourth problem will be the need for experiment with innovations in development procedure. As a nerve center for stimulating research, as the principal "entrepreneur" for large-scale water control, and in several other vital roles, the Federal Government has an important responsibility for timely experiment with innovations in technique, innovations in administrative organization, and other new departures which can improve the efficiency of development and management. A technically coordinated view of the components of comprehensive development will be needed by the Congress, as well as professional study of the strategic timing of support for experiment.

A fifth problem is the provision of means for evaluating progress and reviewing experience in development on an interdepartmental level. In practice the Federal Government in recent years has tended to discharge this important function mainly by assigning responsibility periodically to a temporary agency. Continuance of the present review policy into a future pattern of comprehensive development would leave inadequate coverage for one important step toward efficiency.

A final problem is that of the choice of Federal functions. Future comprehensive water development will be a far more complex planning, entrepreneurial, and management task than anything yet undertaken; the rate of future development also must be at a pace far in excess of any previous experience. Considering the increasing burdens which may be expected to fall on the Congress, and the responsibility that rests on the Congress for many water development decisions, the choice of Federal functions becomes a pertinent question for policy review. The exercise of too many responsibilities by the Federal establishment may be just as discouraging to efficient development as too few. Past experience suggests that basinwide stream regulation, and the leadership for research, pilot plant experiment, and other technical activities can be efficiently discharged by the Federal establishment. On the other hand, the most careful decisions about creating facilities for direct local use of water services are made where local bodies assume a major part of financial responsibility for the enterprise.

Policy suggestions

The report concludes that Federal leadership toward efficient development and use is vital if the national water requirements are to be met between 1960 and 2000. The following suggestions are made for a Federal Government policy which will provide that leadership:

(1) Establish comprehensive development, along the general lines defined in the report, as the procedural pattern for future Federal action in water resource development.

(2) Make the creation or completion of integrated basinwide water regulation systems a primary objective of Federal activity on all streams where physical conditions and the legally determined Federal interest make such regulation appropriate. This course is suggested in a belief that a basic water control system in each basin is at least as important a part of the national productive plant as the national system of defense and interstate highways is to our transportation network.

(3) Simplify the Federal program concerned with direct water use. It is suggested that the Federal Government clearly distinguish direct use projects as primarily for the entrepreneurship of States, municipalities, local public bodies, and private enterprise. Included among such works would be all irrigation pumping and water distribution facilities, local flood prevention and drainage, water quality improvement facilities, water distribution to municipalities, rural water districts, and industrial districts, single-purpose hydropower projects, and water recreation facilities. Where the Congress decides that the national interest is served by Federal stimulation of direct-use projects, Federal participation could be satisfactorily undertaken through grant and loan procedures. A Development Loan Fund to provide low interest loans could be a central instrument to such a policy.

(4) Develop strategy for the growth and application of technical improvement. In particular, recognize that the quality, amount, and direction of fundamental scientific research in certain fields is vital to the progress of water development techniques, and that continuous attention profitably can be paid to the strategy of Federal en-

couragement or support of such research. The objective would be that of recognizing the "growing points" in the advance of science and technology, and seeing that they are applied to water development.

(5) Recognize the need for modernizing and expanding basic data collection in a manner which will serve adequately the future requirements of comprehensive development.

(6) Establish the means for protecting from encumbrance reservoir sites, dam sites, and other sites for future works anticipated as necessary to a program of comprehensive development.

(7) Recognize the future dominant importance of meeting urban industrial requirements in planning the progress of the national water development program.

(8) Recognize that there is substantial opportunity for further consumer benefit through economies of scale in services related to water, particularly in electricity generation and distribution.

Four of these elements of policy could be implemented readily within the existing Federal administration structure. Four others would require careful and specialized study and more deliberate implementation. These are the establishment of comprehensive development, simplifying the Federal program concerned with direct water use, a strategy for technical improvement, and encouraging the employment of related economies of scale. Several first steps toward implementation of the last four elements are: appointment of a small professional advisory staff under joint sponsorship of the Senate (or Senate and House) committees to study thoroughly the application of comprehensive development techniques; an executive branch study of the possibility of simplifying Federal participation in direct-use water projects; an executive branch study of national opportunities for economies of scale in electric power generation and distribution; and the creation of two regional water development study commissions of temporary tenure, one for the nine Southwestern States, and the other for the Northeastern-Midwestern States.

The above policy suggestions have been offered in a belief that they will enable substantial gains in efficiency for national water development, enable full use of scientific and technical resources in future development, permit a higher degree of flexibility in programing than at present, simplify the burden of deliberation and decision on the part of Congress, and provide a clearer division of activities between Federal and non-Federal jurisdictions. It is believed that implementation of these elements of policy could evolve gradually within the existing administrative structure, avoiding disrupting major changes of administrative responsibility.

Finally, policy change should be considered because of the importance of water development techniques as instruments of economic development in our foreign policy. The preeminent position which the United States has enjoyed in this field in the postwar period now is being challenged by the rising technical competence of the Soviet Union and its massive, spectacular projects. For this reason the United States may examine with profit the means of creating a still more advanced overall technique in this country. It is believed that the policy suggestions herein offered may contribute to the evolution of an efficient and highly flexible technique of water development applicable to a wide variety of foreign environments as well as to our own. In its policy choice the Congress has an opportunity to demonstrate alertness to efficiency and advanced technique in a basic public enterprise of peaceful intent.

I. PRESENT DESIGN OF INTEGRATED MULTIPLE-PURPOSE DEVELOPMENT

This report is an evaluation of the effect of future technologic potentialities upon integrated multiple-purpose water development, and an identification of resulting problems of public policy. The period to be considered is chiefly the 20-year interval between 1960 and 1980, but foresighted planning also requires an examination of the 1980–2000 period, insofar as possible. To make such an evaluation one needs to choose and anlyze the techniques themselves, project the economic environment of future water development, and understand the nature of integrated multiple-purpose water development.

Water development, described simply, is the matching of water supply to existing or potential demand for water and water services. In a nation as culturally advanced as the United States, water development is one of the most complex activities undertaken by man. It is complex because the needs for water are universal, and they often are so heavily concentrated in one place that they cannot be met by nearby water supplies. It is complex because many different needs must be served, and these needs often are competing or conflicting, especially in the areas of water scarcity. It is complex because water availability shows wide variations geographically and over time which are ill matched with demands. There are cyclical, annual, monthly, and daily variations in the range of flow of surface waters, the most readily available, commonly used, and valuable of our water supplies. Most streams have minimum flows which are a mere fraction of their maximum discharges, and far below the mean flow. It is complex because water supplies today vary almost as widely in their available quality as they do in available quantity. Water uses also vary widely in their tolerance of suspended solids and dissolved minerals, the two most important determinants of water quality. Finally, water development in the United States is complex because this is a land of large river basins and many tributary basins. The hydrology of these tributary basins is so closely related to all water supply downstream that water uses may become intimately interrelated and interdependent within each major basin.

Under these circumstances careful, professionally planned management becomes imperative. As settlement increases in density and water uses increase in their intensity, it becomes necessary at some point to manage water in such a way that competition among uses is reduced or avoided, complementarity of use is increased, and efforts are made to obtain the maximum amount of services from the water available. In other words, we seek improvement of efficiency [1] in the manner of our water use, as well as justice in its allocation. One way of doing this where water is scarce has been to establish priorities both among individual consumers and among types of use. Thus far, however, priorities have been much more instruments for achieving order and justice in water use than they have been instruments for improving efficiency.

The outstanding instruments thus far developed in the United States to promote improvement of efficiency have been the techniques of integrated multiple-purpose design and management. Considered from a public point of view their advantages already are so well proven that they inevitably will be the foundation upon which future improved planning and management will be built. They are absolutely fundamental to any future national review of public policy in water development.

The basic physical means for improving the efficiency of natural waterflow to meet economic demands are regulation works, principally storage reservoirs. The reason for storage is the detention of surplus waters until they can be used, or the conversion of natural streamflow patterns into the more useful regulated flows. Such detention may be undertaken either for a single purpose or for two or more purposes. Multiple-purpose storage (and release) has proven far more economical than a series of single-purpose works because: (1) It increases the scale and lowers the capital costs of storage, (2) It takes advantage of complementarity among uses and thereby increases the range of services available from a unit of storage. It also lowers operational costs for the same reasons. When several different purposes are served by flow regulation works, as a storage reservoir, a larger installation may be possible than for single purposes. Lower capital costs per acre-foot of water, per-kilowatt hour of electricity, and for other services are achieved. Some "scale economies" thus are attainable through multiple-purpose design and operation. In addition, the same reservoir storage space to some degree may serve different purposes at different seasons, thus yielding economies from complementarity.

A basic unit in integrated multiple-purpose development therefore is the multiple-purpose surface reservoir. Multiple-purpose surface reservoir operation essentially is the synchronization of water detention and release with two or more types of demand which may be incident upon a single flow or a single source of water. The operational objective is that of scheduling supply so as to produce maximum net benefits. This is done by increasing complementarity and reducing competition among uses. An ideally managed water supply would have all possible uses brought to such a condition of complementarity that the maximum economic and social benefits would be produced for the investment and operational costs incurred. Institution of multiple-purpose reservoir management always is a step in this direction. In the United States the principal development purposes around which multiple-purpose operation has been planned are irrigation, navigation, flood prevention, and electric power production. Development for these purposes, however, must be consistent with the long-established priorities of domestic water supply. Still other purposes are of increasing importance for multiple-purpose management: industrial water supply, waste carrying, and recreational use.

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[1] Efficiency is defined in sec. III, p. 13.

Although development and management for all of these purposes is needed in few localities in this country, development for a majority of them in differing combinations is a certain need in all densely settled sections of the country.

The second important technique for increasing the efficiency of a natural water supply is the interrelated operation of two or more units of storage or supply in an integrated system. Some important advantages of large-scale operation of water facilities may be achieved by the construction of large individual structures for multiple purposes; these advantages often may be greatly enhanced through the technique of merging operation of two or more units of supply into an integrated system. Economies of scale again are possible.[2]

Integrated operation is the management of a system of complementary facilities under a single, overall control (not necessarily under single ownership) in the manner which maximizes the combined net benefits from the operation of the individual reservoirs and other facilities. Integrated operation will yield considerably more than the sum of benefits from the component facilities independently managed. Two varieties of integrated operation may be distinguished: fully integrated operation of a complete system under a single management, as in the Tennessee Valley; and coordinated operation of facilities by joint agreement among several agencies, as on the Columbia River. The differences between these two varieties will not be evaluated here. It suffices that they are dedicated to the same principle. Either method demonstrates clearly the scale economies to be achieved within a single river basin by integrated system operation of facilities.

Ideally a system of reservoirs is designed with built-in flexibility for integrated operation. However, even a set of separately planned works, so long as they are in the same basin, may be operated in an integrated manner with some gain in net benefits.

Integrated operation also may and more frequently will, include subsurface storage facilities. Recognition of the unity of surface and ground water resources is a logical extension of design and management on an integrated pattern. As Loehnberg has observed, the planned manipulation of ground water greatly extends the usefulness of river basin development.[3] Ground water storage near the middle or upper reaches of streams can add substantially to the system economies of a series of reservoirs.

A third means of improving the efficiency of natural water supply is the interconnection and integrated system operation of regulating facilities in two or more river basins. This is brilliantly conceived and most clearly illustrated in the California State Water Plan of interconnection and water exchanges reaching from the Trinity River of northern California to the Imperial Valley of southern California. Applied to only a few situations thus far this step is likely to receive more frequent attention in future U.S. water development.

This report accordingly commences with three assumptions. They are: (1) Improvement of the efficiency of water supply to the extent required by long-term needs will be one important public objective in water development.[3a] This will mean planning and operation of projects so as to attain maximum net benefits from all purposes. (2) Multiple-purpose regulation is an indispensable technique for improving efficiency. (3) Integrated system operation of regulation works is a second indispensable technique, which will be an accepted form of eventual management for every intensively used river basin. Conversion of existing separately operated works into integrated systems is included. In some situations of water scarcity or intense demand integrated system operation will apply to regulation works located in two or more basins.

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[2] It is here assumed that the efficiencies of integrated multiple-purpose development are common knowledge and that detailed proof need not be offered for the above statements. If brief reference to such proof is desired, see E. A. Ackerman and G. O. G. Löf, "Technology in American Water Development," Johns Hopkins Press, Baltimore, 1959, pp. 192-194, 244-248.

[3] Alfred Loehnberg, letter to the author, March 3, 1960.

[3a] There also may be, and certainly will be, other public objectives in development, along with efficiency. However, the major influences of technology touch efficiency most closely. Reference to improvement of efficiency therefore will be prominent in this report.

II. THE FUTURE TECHNICO-ECONOMIC ENVIRONMENT IN WHICH WATER DEVELOPMENT WILL BE UNDERTAKEN

We have just stated an underlying assumption of the report: one basic public objective in water development will be the improvement of efficiency of water supply to the extent required by long-term needs. Since this assumption obviously permits some flexibility in interpretation, a summary evaluation of long-term needs is essential to any analysis of the relation of technology to integrated multiple-purpose development in the period 1960–80. In other words, an understanding of the nature of the future technico-economic environment of the Nation must be at hand to answer the question: *to what extent* will the Nation seek efficiency in water development?

Even though the period to be considered here is that of 1960–80, the likely technical and economic environment of years beyond 1980 also should be considered. The longer view is necessary because the form of water development for decades ahead is set in any major program decision. Obviously a number of decisions which will greatly influence the form of 1980-2000 water supplies will be made between 1960 and 1980. These decisions especially will be encountered in planning integrated multiple-purpose development.

There are six features of the technical and economic environment which may give clues as to likely future pressure for improved efficiency in

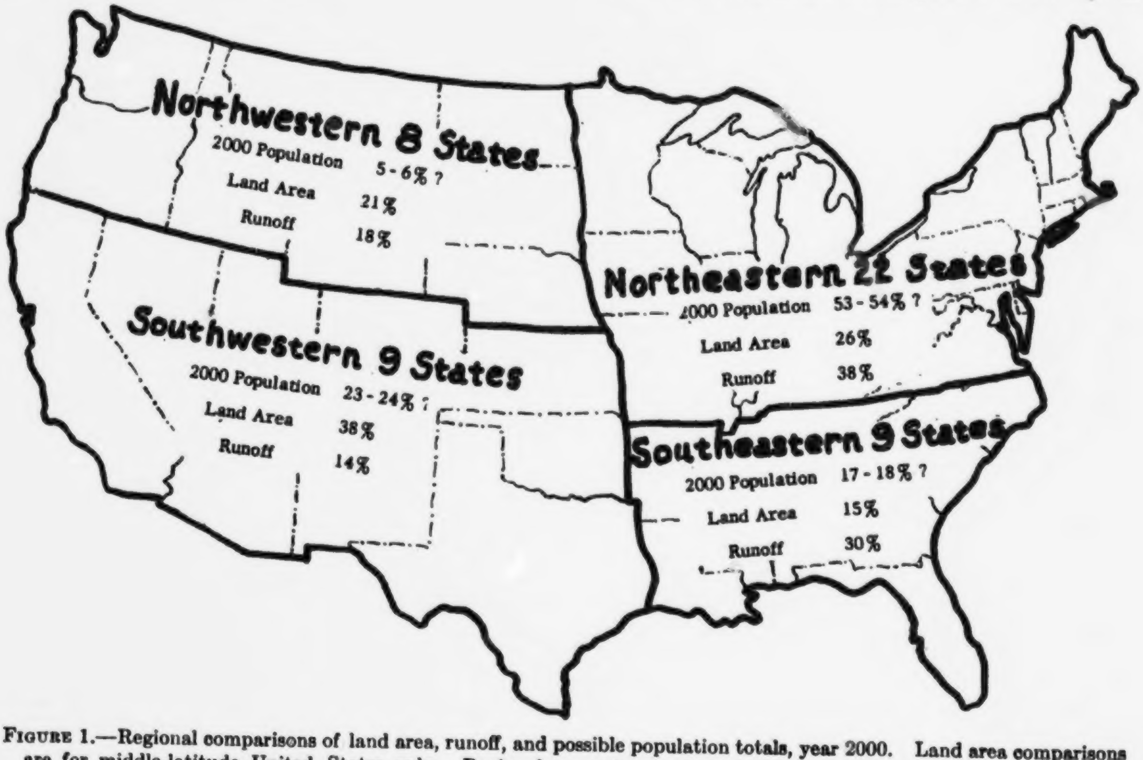

FIGURE 1.—Regional comparisons of land area, runoff, and possible population totals, year 2000. Land area comparisons are for middle-latitude United States only. Regional percentages of total U.S. population as estimated for 1958 (173,260,000) were: Northwestern States 5 percent; Southwestern States 19 percent; Northeastern States 59 percent; and Southeastern States 17 percent.

water development. They are: (1) The people of the United States—their total number, their location and mode of life, and their level of wants; (2) the size, type, and location of manufacturing industries; (3) the nature and location of agricultural production; (4) other aspects of land use influencing water requirements, as, for example, national defense establishments; (5) the general rate of technical progress in the Nation; (6) continued spread of land use planning at lower governmental levels.

Population [4]

Compared to the present population of approximately 179 million in the United States, Census Bureau estimates place the national total for 1980 somewhere between a low estimate of 230 million and a high estimate of 272 million. Similar projections to the year 2000 bring the totals for that not-so-distant year to a range between 293 million and 417 million. Thus it seems entirely possible that the population of the United States will be doubled by the year 2000, and even the minimum estimate indicates an enormous increase. A high percentage of these people will be urban residents, dependent upon urban pursuits. The time is likely to come within the century when not more than 5 percent of the country's total population will be directly supported by primary agricultural production. While any estimate of the regional location of total population is subject to a wide margin of error, a generalized breakdown could logically place 70 to 71 percent of them in the eastern 31 States, 23 to 24 percent in the southwestern 9 States, and 5 to 6 percent in the northwestern 8 States (fig. 1). Furthermore, it is likely that more than half of the population will be concentrated in two very densely settled areas, the industrial belt of the Northeast and Midwest, and in California (fig. 2). Probably 60 percent of the total

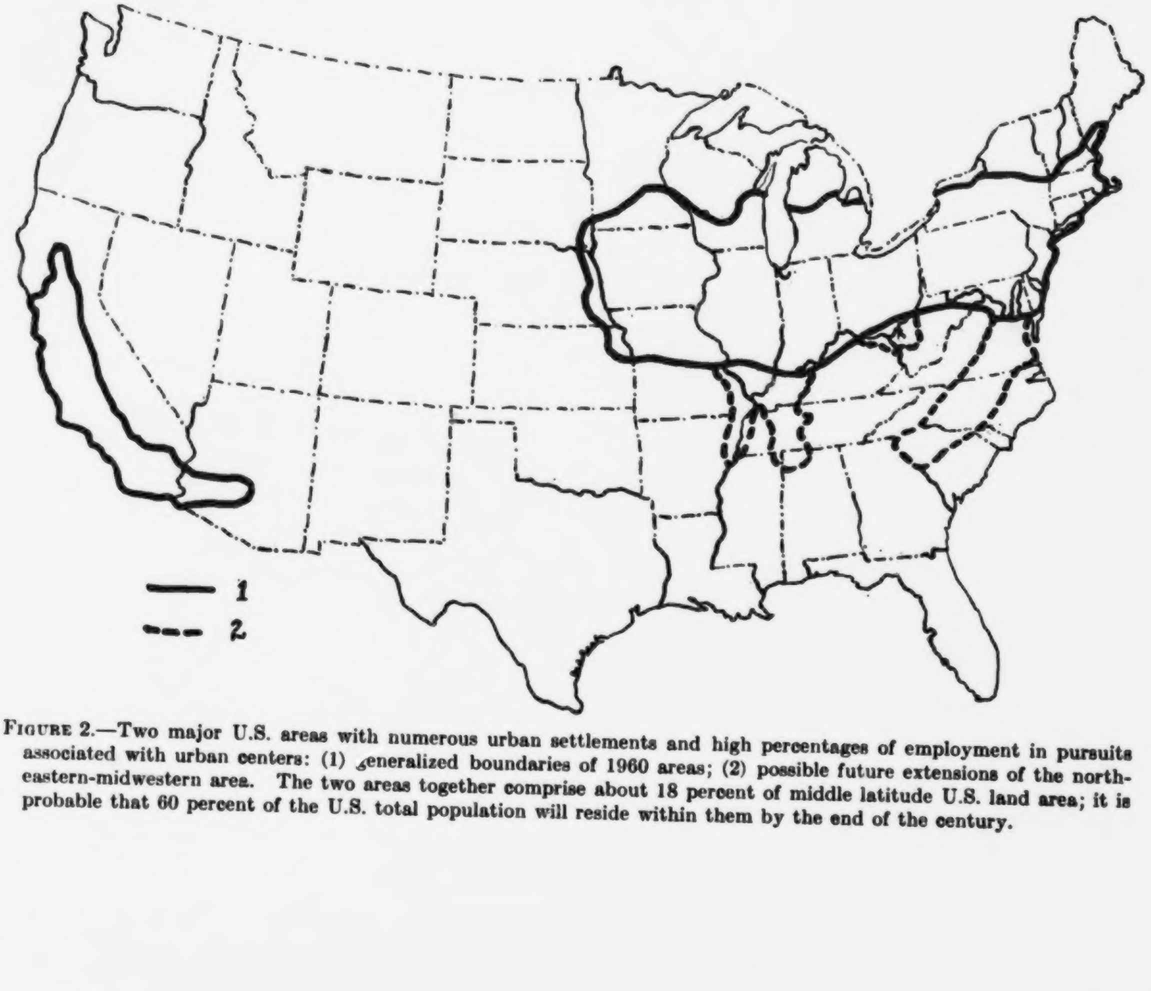

FIGURE 2.—Two major U.S. areas with numerous urban settlements and high percentages of employment in pursuits associated with urban centers: (1) generalized boundaries of 1960 areas; (2) possible future extensions of the northeastern-midwestern area. The two areas together comprise about 18 percent of middle latitude U.S. land area; it is probable that 60 percent of the U.S. total population will reside within them by the end of the century.

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[4] See also app. 1.

population will be in these two areas, which together comprise only 18 percent of the country's land area (Alaska and Hawaii excepted). There are many indications that levels of living, and therefore levels of consumption, also may be expected to rise notably. Resources for the Future estimates place the 1980 per capita gross national product at 1½ times that of 1959, and that of 2000 at 2.4 times the 1959 level.[5] There also is every indication of impending decrease in the number of working hours, and, therefore, increase in the amount of leisure time available to the average person during these years.

The location of manufacturing industries

Only a qualitative estimate of the relative concentrations of manufacturing in the several regions of the country will be attempted. Quantified projections rest on so many assumptions that they have little value for periods beyond a few years. Two features of future manufacturing location seem certain enough to be adopted as basic assumptions in planning:

(*a*) A dominant part of future manufacturing employment will continue to be concentrated in two areas. These are the great manufacturing belts of the already industrialized Northeast and Midwest, and central and southern California. The borders of the northeastern-midwestern area are likely to be moved in directions expanding the area, particularly in a southerly direction. However, the opening of the Great Lakes to deeper draught ocean traffic may also cause some westward expansion of this same belt.

(*b*) A much wider dispersal of manufacturing industries throughout the United States may be expected at the same time. This dispersal will take place both within the two densely settled great urban areas and extend to most of the less densely settled States. This is assured by the almost revolutionary transportational changes which will be caused by construction of the 41,000-mile National System of Interstate and Defense Highways (fig. 3), by the certain and substantial additions to labor force in almost every State which will not be absorbed by agricultural or extractive occupations, by the active and increasingly sophisticated efforts of nonindustrialized areas to establish manufacturing plants, by the development of hydroelectric power in the Pacific Northwest, and by the increasing dependence of this country upon foreign sources of minerals and other raw materials. Some secondary concentrations of industrial activity are likely to be intensified, as in the Oklahoma-eastern Texas-Louisiana area. While technical trends make it certain that the service occupations will increase relatively more rapidly as sources of employment than manufacturing, it is also certain that many more communities in nearly every State will be intimately concerned with the existence of and the problems attending manufactural output.

The nature and location of agricultural production [6]

The United States is now and increasingly in the future will be an urban entity; that is where the heart of its economic life will be. Furthermore, the mechanized, chemical-fed, research-based agriculture of today and the future is inseparably bound to the city. And farming will be a direct source of livelihood for only a minor proportion of the Nation's people. In spite of these facts agriculture is likely to continue as a front-rank consumer of water. Some separate evaluation of its future, therefore, is needed. Three aspects of the Nation's future agricultural industry would seem to bear upon future water development planning: (*a*) The volume of future agricultural production, (*b*) the management of objectives of the Nation's farms; and (*c*) the regional location of future additions to producing capacity.

The population projections alone lead to the conclusion that a very large increase in agricultural output during the next decades is likely, if not essential. An output more than double that of the present day must be entertained as a possible requirement sometime during this century.

No reversal of the increasing trend toward specialization in agriculture is foreseen. Family farms are likely to contribute a minor part of total farm production, and realistic planning probably will look at agriculture as part of a complex interdependent industrial system centered on urban areas.

Location of additions to the future agricultural plant is likely to be affected by the location of

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[5] Per capita gross national product (approximate): 1959—$2,777; 1980—$4,320; and 2000—$6,650. See "Resources for the Future," annual report, 1959.

[6] See app. 2 for additional comment.

THE NATIONAL SYSTEM OF INTERSTATE AND DEFENSE HIGHWAYS

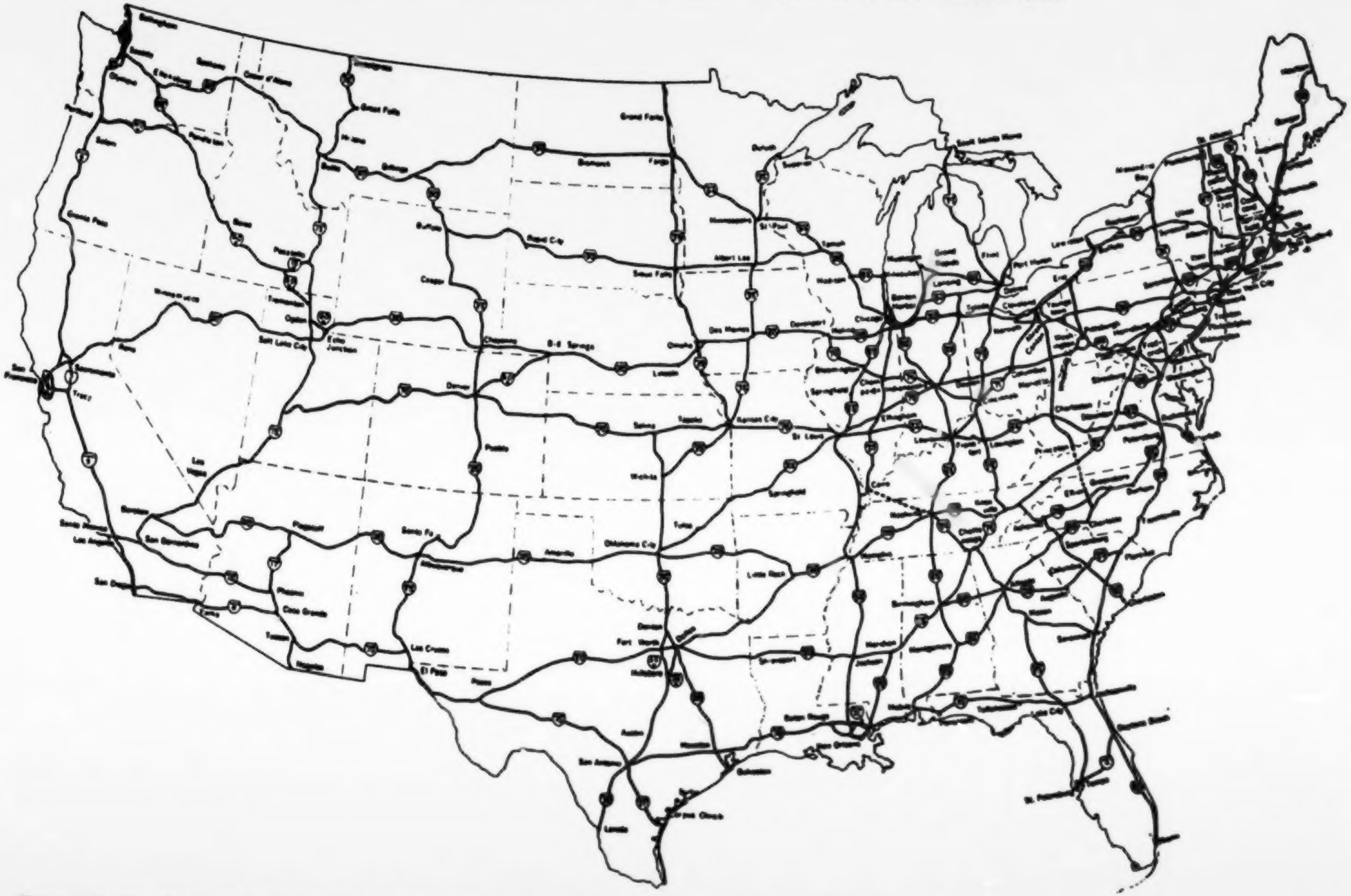

Figure 3. The National System of Interstate and Defense Highways (U.S. Department of Commerce, Bureau of Public Roads, September 1959).

population. It is reasonable to expect two-thirds of the great population growth anticipated, whatever its exact size, to take place east of the Mississippi River. The great markets for farm products will continue to be in the 31 Eastern States. This cannot fail to influence the future location of increased agricultural production. The attraction of these great future markets is reinforced by the physical location of the country's resources—41 percent of the land area and 68 percent of the stream runoff are located in the eastern 31 States.

Other aspects of land use influencing water requirements

At least several other factors must be anticipated in any judgment on the need for efficiency in future water development. These will be illustrated briefly by reference to future residential land use, location of defense establishments, and need for resource bases for service occupations.

The astonishing dispersal of residential land use over the countryside adjacent to almost all U.S. cities in the last 15 years has brought many local water problems. When the interstate expressway system is completed, further dispersal may be expected. In addition, space must be found for the tens of millions of added population who will be engaged in nonagricultural occupations. Further spread of urban and suburban land use is certain to be a compelling phenomenon of the remainder of the century.

One additional feature of residential land use is the likely continued attraction of sections of the country possessing climatic amenities for permanent residents, regardless of existing water resources or employment opportunities. The correlation of this attraction with an increased percentage of older people in the total population is of interest. The attraction of climatic amenities is of particular importance in planning for the nine Southwestern States, and to a lesser degree in the Southeastern States.

For a variety of environmental reasons including both space and climate, many defense establishments have been admirably located in the Western States. Again to a lesser extent some Southeastern States also have been favored in this respect. There is little reason to see a reversal of this attraction, which may even be enhanced by the transportation facilities afforded by the new expressway system.

Technical trends reducing the amount of labor and employment needed for both manufactural and agricultural output press the Nation toward a problem of finding increasingly larger employment outlets in service occupations. The planning of water resource development with needs for service industry employment in mind might be considered a foresighted and wise course. Proper attention to the recreational possibilities of all water development may be basic contributions to employment planning as well as contributions toward meeting the vastly increased needs of urban areas for recreational outlets.

The general rate of technical progress in the Nation

It is now a commonplace that technical innovation creates problems, sometimes grave problems, of social adjustment. Problems of resource use resulting from technical change have been of no small concern from "the plow that broke the plains" to the waste chemicals which find their way into modern stream courses and aquifers. Even more, technical innovation has been the source of improvements in resource use. Consequently, some indication of the rate of technical change is an important part of judging the efficiency of development, or the need for efficiency. The important question here is: Can the rapid rate of technical change of the recent past be projected for the remainder of the century?

There are good indications that the rate of technical innovation experienced in the past not only will continue but will be astonishingly accelerated. Dr. Caryl P. Haskins, president of the Carnegie Institution of Washington and former member of the President's Science Advisory Committee, speaks of "the incomparable richness of innovational opportunity in our time."[7] He notes further that "the cycle from discovery to opportunity to new discovery is self-accelerating, in its later phases reaching explosive dimensions."[8] He goes on to say that in England there has been a doubling of the volume of scientific effort about once every 10 to 15 years, or three times in a generation.[9] That a similar process is going on in the United States is roughly indicated by the total expenditures formally cataloged for research and development in the Nation. For 1958 they were more than three times those similarly recorded for 1950. Expenditures for research and development performed by private industrial firms in the United States more than doubled between 1953 and 1957.[10] In 1959–60 they will be 2½ times what they were in 1953–54.[11] It has been forecast that the decade of the 1960's will show a threefold increase in research and development expenditures over that of the 1950's.[12] As Dr. Haskins says, "these are massive and colorful factors shaping and scaling our future opportunities for innovation." Thus it seems more than likely that technical innovation in the decades immediately ahead may be not only at an accelerated rate but at a greatly accelerated rate compared to that of the immediate past. Recognition of this general characteristic of the years ahead will be vital for successful planning.

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[7] "Carnegie Institution of Washington Year Book, 1957," Washington, D.C., 1958, p. 3.

[8] Ibid.

Land-use planning

One further feature of the future economic environment likely to influence water development efficiency is the steady progress of land-use planning in the United States. Even though the encouragements toward land-use planning organized nationally under the National Resources Planning Board were abandoned in 1943, land-use planning has made steady progress since the end of World War II in both urban and rural areas. Such planning has become increasingly important at lower jurisdictional levels in the country. It may be illustrated by the growth in active soil conservation districts and by the growth in numbers of professional planners since 1945, and by the number of communities having active planning agencies in 1959 (tables 1, 2, 3). Still further indication of an interest in planning may be seen in the existence of many local "area development" agencies. More than 12,000 were reported in 1959.[12a]

Within the last few years almost every month has brought some significant expansion of land-use planning activities on the part of towns, suburban counties, cities, metropolitan areas, States, and rural counties.

TABLE 1.—*U.S. soil conservation districts, 1938–59*

Fiscal year (July 1–June 30)	Districts organized		Total area in districts (thousand acres)	
	By individual year (net addition)	Cumulative total at end of year	New districts and additions to previously organized districts	Cumulative total at end of year
1938	69	69	36, 107	36, 107
1940	153	314	101, 306	189, 752
1945	232	1, 346	120, 368	740, 859
1950	121	2, 285	74, 721	1, 253, 484
1955	56	2, 674	43, 478	1, 484, 974
1959	55	2, 861	28, 650	1, 661, 968

Source: Soil Conservation Service, "Report of Administrator of Soil Conservation Service," for years listed.

TABLE 2.—*Planning agencies in the United States, 1945–58*

	1945	1950	1955	1958
State [1]	(2)	(2)	(2)	40
Metropolitan or regional [1]	(2)	(2)	(2)	78
County [3]	[3] 100	(2)	(2)	[3] [4] 500
Municipal (total) [5]	538	668	716	973
Over 1,000,000 population	5	5	4	5
500,001 to 1,000,000	9	9	10	12
250,001 to 500,000	22	23	21	22
100,001 to 250,000	45	47	56	59
50,001 to 100,000	74	84	95	112
25,001 to 50,000	153	150	161	223
10,000 to 25,000	230	350	369	540

[1] Source: American Institute of Planners.
[2] No data available.
[3] Estimated by National Association of County Officials for official planning agencies only. By 1959 most of the remaining 1,500 counties in the country had some type of unofficial planning agency.
[4] 1959.
[5] Source: "Municipal Year Book," International City Managers' Association, Chicago, 1959.

TABLE 3. *American Institute of Planners Membership, 1945–59* [1]

1945	244
1951	1, 033
1955	1, 326
1959	[1] 2, 300

[1] Estimated to be about ¾ of practicing professional planners in the United States in this year.

Source: American Institute of Planners, files.

This trend illustrates the nearly invariable rule in the past of this country that as the demands and competition for a resource increase, planned use has arisen. Such competition has been much in evidence since the end of the war in agriculture because of mechanization and other factors which have greatly increased agricultural labor output; it also has been characteristic of urbanized areas with their swollen tides of new residents.

There is no reason for believing that the trend toward more widespread land-use planning by local governmental units will be reversed in the future. Indeed, it is likely to be intensified, under the impact of the vastly increased density in settlement and the resulting competition for land use. This means that large numbers of people, perhaps a majority of the residents of the United States, are likely to live in areas where land-use planning is an accepted part of everyday living. From land-use planning on a community or county basis, it is but a short step to integrated development of small watersheds. Indeed, the two often are inseparable, as the growing interest in small watershed development illustrates. Once they have reached any degree of widespread coverage within a river basin, land-use planning and small watershed development are certain to raise questions of water use and water control which only can be answered by planning water development on an integrated basis.

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[9] "Carnegie Institution of Washington Year Book, 1955," Washington, D.C., 1956, p. 6; "Carnegie Institution of Washington Year Book, 1958," Washington, D.C., 1959, p. 8.

[10] National Science Foundation, "Reviews of Data on Research and Development," No. 14, NSF-59-46, August 1959, 6 pages. If the aircraft industry is excepted, about one-fourth of the expenditures was federally financed in 1957.

[11] National Science Foundation news release, Dec. 26, 1959.

[12] "Carnegie Institution of Washington Year Book, 1958," Washington, D.C., 1959, p. 8.

[12a] D. R. Gilmore, *Developing the "Little" Economies*, Committee for Economic Development, New York, 1960.

Summation of reasons why efficiency will be sought in water development

There is no doubt that potent pressures for efficiency will exist in future U.S. water development. The only real question asked is whether this pressure will be met by response to crises or whether it is met in advance by foresight and planning. Every indication points toward needs for the organization of water supply and the services which can be provided through water development on a scale and at a rate not thus far experienced in this country. The large total growth of population, the change to a heavily urban population concentrated in dense settlements of vast proportions, the dispersal of industry and residential settlement, changes in our occupational structure and habits of leisure will create requirements which can be met only through efficient development. These pressures may be supplemented by movements toward locally organized efficient use of land. In fact, the need for efficient development will be greater than ever before, spurred as it will be by unprecedented total annual increases in population, and by an accelerated rate of technical change. Few parts of the country are likely to be immune from this pressure at some time during the remainder of this century. For the Southwestern States and for the northeastern-midwestern urban zone the pressures are obvious; the ratio of population to local resources in both areas will be high. However, the need for well managed water supplies brought by dispersed industrial growth and by the need for continued expansion of agricultural production will bring the same pressures, if in a lesser degree, to the other regions. These pressures or needs may be interpreted as meaning: (*a*) Water of the quantity and quality essential to the establishment of manufacturing and service occupations required for full employment of each region's labor force. (*b*) Water, water facilities, and water-derived services required to provide the popularly expected amenities of normal living. Besides recreational facilities these may be considered to include low-cost electricity. (*c*) Water in quantity and quality adequate to support the required production of food and other agricultural products. (*d*) Water facilities to the extent needed to provide transportation facilities at optimum costs for the Nation.

III. The General Relation of Technologic Change to Efficiency in Water Development and Water Management

In the preceding section environmental reasons were given for the growth of pressures for efficiency in water development and management during the 40 years 1960–2000, and which must be considered between 1960 and 1980. The forms which those pressures may take have been described briefly. The first assumption stated at the end of section I therefore is accepted as valid: A basic public objective in water development will be improvement of the efficiency of water supply. It therefore becomes desirable to define efficiency.

Very simply defined, efficiency is the relation between the amount of input and the amount of resulting useful output. The larger the useful output per unit of input, the more efficient the process.

In water development and management illustrative actions directed toward improvement of efficiency would be measures which reduce waste of water, design of dams which reduces storage costs per acre-foot, and measures of management which increase complementarity among competing uses. It must be noted that considerations of efficiency are always related to some predetermined objective or objectives. In water development and management this might be an increase in gross national product, an increase in regional income, an increase in income for a particular producing group, additions to outdoor amenities, or still other changes. Definition of these objectives is beyond the province of this report. Instead, it is the purpose of the report to examine the means which may be made available by technologic advance for increasing efficiency of water supply *whatever specific objectives are chosen by the Congress*. However, these objectives must ultimately be defined and understood if improvements in efficiency are to be meaningful.

It is essential to understand that regional and local water shortages of varying degrees of seriousness can appear and may be forecast for the future of the United States. However, the multiplicity and versatility of modern techniques of planning, development and operation are so great that if they are properly applied in time, crises may be avoided and all requirements may be at least adequately and probably well served.

TECHNIQUES WITH POTENTIALS FOR EFFECTING INTEGRATED MULTIPLE-PURPOSE DEVELOPMENT

As new demands arise in the future, they may for a time and everywhere be met by extensions of existing practice, particularly as existing practice of integrated multiple-purpose development is applied. It is even likely to serve indefinitely for some few areas without modification. In addition, there are certain windfall events which may be depended upon to improve the efficiency of future development which remain unseen and unsusceptible to evaluation until they appear. A notable example of this in the recent past was the perfection of high-capacity earthmoving equipment. On the other hand, these windfalls cannot be depended upon to solve the huge problems of matching supply and demand which can be foreseen in the years ahead. A methodical evaluation of technical possibilities therefore may assist in meeting public responsibilities. These possibilities may be sought in: (*a*) improved planning, design, construction and operation of systems of integrated multiple-purpose works; (*b*) exploration for, discovery, and exploitation of new supplies; (*c*) conservational and other measures for reducing requirements; (*d*) treatment of waters having substandard quality. Thus conscious steps toward efficiency are to be sought both in an improvement of the techniques of integrated multiple-purpose development themselves and in supplementing them with other measures.

A summary is presented in table 4 of certain aspects of new technology related to future efficient water resource development thought to be of interest to the select committee in its policy study. Brief notation is made in the table of the estimated earliest state of first practical application of a technique, the water development purposes most affected by the technique, the geographic regions most affected, the added water supply, water savings, or other economies, the present status of research or use of the technique, and suggested strategic immediate action concerning it. Although the minimal essential information for policy consideration in this field is contained in table 4, some further elaboration and emphasis are appropriate. The succeeding discussion will follow the headings given in the table in order.

Planning design, construction, and operation of systems of multiple-purpose works

Among the many spectacular technical developments of the last 20 years there has been a quiet one with relatively little news appeal. Nonetheless it has been revolutionary, and yearly it is becoming more pervasive. This is the application of methods of rigorous formal analysis based upon mathematical thought to planning, design, and operational problems which have interdependent variables.

TABLE 4.—*Some techniques related to future efficiency of U.S. water resource development*

	Estimated earliest date of 1st practical application	Water development purposes affected	Geographic regions most affected	Added water supply, savings, or other economies	Present status	Strategic immediate action
(a) Planning, design, construction, and operation of systems of multiple-purpose works:						
1. Systems analysis, linear programing, etc., applied to basins.	1961-64	All	Any watershed or river basin.	Substantial investment savings and contributions to operating efficiency possible.	Simple systems have been explored experimentally.	Application to actual planning on small- and medium-sized watersheds.
2. Consumption models, applied geography.	1962-64	All	All	Timely preparation for meeting requirements.	1 water analysis made, techniques most applied to transportation.	Employment and income maximizing studies by State or basin. Study of navigation.
3. Prognostic hydrology	Some in 1960.	All	All	Reduce risk of overbuilding, substantial savings in planning production if cyclic moisture fluctuation understood.	Some research and experiment.	Considerably expanded fundamental research.
4. Materials economizing design of hydraulic and accessory structures.	Previous to 1960.	Some	All	Not presently evaluable.	European and American prototypes of materials economy are in existence.	Consulting technical review of designing practices.
5. Use of nuclear explosives and other unorthodox engineering approaches to underground storage, and other earth and rock movement.	Not presently evaluable.	Irrigation, industrial, domestic water supply, pollution control, navigation.	Western States	Not presently evaluable.	Atomic Energy Commission has experimented with underground explosion, other experiments in planning stage.	(a) Further nuclear experiment under AEC direction. (b) Further study of geology of underground storage.
6. Water pipeline and other movement techniques.	Previous to 1960.	All consumptive uses.	West	Facilitates interbasin movement.	Available	
(b) Exploration for, discovery and exploitation of, new supplies:						
1. Weather modification	Some previous to 1960.	All	Western States	Annual addition of 15,000,000 acre-feet to supply.	Much empirical experiment. Recent expansion of research.	(a) Added fundamental research. (b) Pilot experiment in entire river basin. (c) Economic study.
2. Geophysical and other exploration of unknown aquifers.	Previous to 1960.	Irrigation, industrial, and domestic water supply.	Western States	Billions of acre-feet of ground water available on "mined" basis.	Methods available	Field study.
3. Appraisal of ground water movement.	Previous to 1960.	Irrigation, industrial, domestic water supply, and pollution control.	All	Not evaluable	Method needs further development.	Further laboratory, experiment, and field study.
4. Lifting ground water to surface.	Not evaluable.	Withdrawal uses in localities dependent on ground water.	Western States; Atlantic and Gulf Coastal Plain.	Goal: lifting water economically beyond 1,000-foot depths.	Private companies have development programs.	(a) Public support of promising engineering experiment. (b) Study of local energy costs.
(c) Measures for conservation and reduction of demand:						
1. Recycling	Previous to 1960.	Industrial water supply.	All	Probably 200,000,000 acre-feet of withdrawal annually, thus saving investment costs on storage, against which treatment costs to be charged.	A variety of techniques are known.	Study of comparative economies of storage and recycling needed.
2. Water-conserving agronomy.	Previous to 1960.	Irrigation	Western States 1960–80; 1980–2000, also Southeastern States.	Not presently evaluable because of large variation of local agronomic environments.	A variety of techniques are available, but few methodically related to water supply problems.	(a) Technical evaluation of water-conserving aspects of agronomy to direct further research. (b) Experiment with known techniques as a part of watershed and basin management
3. Forest and range management for water yield.	1965?	Irrigation, industrial, and domestic water supply.	Western States	Not presently evaluable.	Experiment underway.	Continued experiment and economic evaluation.
4. Evaporation suppression.	1963?	All	Western States	Goal: water saving of 10,000,000 acre-feet.	Experiment underway.	Continued experiment
5 Planned location of demand by publicly controlled land use.	1960	All	All	Substantial reduction in public investment costs theoretically possible.	Techniques known, local acceptance growing.	Study of the economics of planned land use related to water development.

TABLE 4.—*Some techniques related to future efficiency of U.S. water resource development*—Continued

	Estimated earliest date of 1st practical application	Water development purposes affected	Geographic regions most affected	Added water supply, savings, or other economies	Present status	Strategic immediate action
(*d*) Treatment and use of waters having substandard quality:						
1. Treatment of organic wastes producing a biological oxygen demand.	Previous to 1960.	Domestic and industrial water supply; recreation; fish and wildlife.	All	Can avoid very large, and economically inestimable losses from pollution	Techniques known, but local hesitance about capital expenditure can create many future problems.	(*a*) Further experiment with reduction of treatment costs and use of reclaimed water. (*b*) Study of means of accelerating provision for treatment.
2. Greatment of chemical wastes.	Previous to 1960.	All withdrawal use; recreation; fish and wildlife.	Manufactural localities; some in suburban residential localities.	Same as D–1 above.	Some unsolved technical problems, as in detergent use.	(*a*) Further research and development of practical treatment processes. (*b*) Establish minimum standards of effluent quality. (*c*) Study of means for monitoring water quality.
3. Decontamination and disposal of radioactive wastes.	1960	All except navigation.	All	Not evaluable	1960 risk of contamination small.	Continued study of control and preparation for an economy with wider use of nuclear materials.
4. Desalting sea and brackish waters.	Some in 1960.	Domestic and industrial supply; possibly irrigation at an undetermined future date.	Great Plains, Great Basin, Tex., Calif.	Depends on success with cost reduction; potentially large added supply.	All present operating processes high cost; varied experiment underway.	(*a*) Expansion of fundamental research; continuation of pilot plant program. (*b*) Study of needs for desalted water.
5. Sediment control	Some previous to 1960.	Same as d-1 above.	All; of most immediate interest in West and Southeast.	Large economic savings; esthetic values.	Widely used processes in municipal water supplies.	(*a*) Continued erosion control. (*b*) Research and experiment directed toward large-scale low-cost elimination in water.
6. Use priorities corresponding to water quality.	Some previous to 1960.	All withdrawal uses.	Northeaster-midwestern urban area; Western States.	Substantial in water-scarce districts, but at some economic cost.	Salt waters and sewage effluent already used in some localities for manufacturing, electricity generation and agricultural use.	(*a*) Methodical study of quality tolerance of water uses. (*b*) Further experiment with means for using mineralized water.

Integrated multiple-purpose development is basically a problem in the efficient organization of interdependent units within a system. Hence those tools which have been proven as applicable to organizational efficiency are certain to be applied to this field in the future. They may generally be grouped as the techniques of "operations analysis" or "systems analysis."[13]

The application of these techniques will be particularly important as the need for interbasin systems arises more frequently in the future.

Operations analysis has been greatly aided by the development of mechanical systems of computation represented in the large analog and digital computers. Linear programing is perhaps the most familiar among these methods, having been widely applied to problems of defense organization during the last war and now to a great variety of industrial planning and operational activities. Others are probability analysis, and more recently game theory. It is virtually certain that some of them can be applied with resulting gains in efficiency to integrated multiple-purpose development in the future, from the small watershed to the large river basin. These methods promise to be of great assistance in achieving future design of systems of water control facilities, or, for that matter, a lone multiple-purpose work. They also may be applied to the evaluation of other techniques in combination with integrated multiple-purpose development.

It must be stressed that operations research methods can aid in setting objectives, but they in no way eliminate the need for public policy decisions on objectives. There is no need for the Congress or other public bodies to fear any arrogation of policymaking function by technical planners through the future application of these methods. Indeed they are best applied to problems in which an objective has been clearly set prior to the analysis.

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[13] See app. 3 for a brief description.

The field for their application may come at any level, depending upon the objective chosen. The following may illustrate the possible application of these methods to system design.

Suppose that the Congress decides that in the future development of a given U.S. river basin a principal objective is to be the provision of full employment for the labor force of the State or States within the given river basin by the year 1980 (or any other chosen year). One qualifying restraint is that employment should be so provided that existing income levels will be equaled or exceeded at the future date. Appreciation of the value of such an objective is entirely possible at some time in the not-distant future. As population grows, the connection between resource use and employment in most regions is certain to demand attention. For water the question might typically be: what is the "mix" of irrigation, industrial use, water recreational facilities, and other use which will allow the attainment of the objective posed? One answer could be provided through an arbitrary decision made from existing knowledge about man-days of employment provided by an acre-foot of water used in agriculture, differing types of manufacturing, and other use. Such an answer is in the nature of an intelligent guess.

Although they have been little tried thus far, formal analytical methods can give a more precise and dependable answer than the arbitrary decision. Assuming the social objective of full employment stated above, operations analysis techniques can assist by increasing the precision of planning and design, and by guiding system operations toward high output after facilities have been built. Planning might begin with consumption model study, in which the employment effects of several different "mixes" of water use would be tested. One of the "mixes" presumably would show a combination of employment effects approaching those which had been set in the congressional objective. This model, with its estimate of quantities of water needed for the several purposes to attain the objectives, would be the basis for the physical planning of required future water development. Similar methods can be applied in the determination of land-use effects of water development through the methods of applied geography. No study of water projects along this latter line has yet been undertaken, although the methods have been applied to similar cases of highway development.

At this point, the traditional method of the past would be one of applying engineering experience and hydrologic data in a set of cut-and-try designs, arrived at by hand calculation. Engineering experience will guarantee the design of a good system of facilities, but the laboriousness of hand calculations places a definite limitation on the number of alternatives which can be examined in the design. The probability that the best system will have been arrived at is low.

One operations analysis approach to the same problem of physical design would simulate streamflow or other hydrologic characteristics on a high speed digital computer. A great many alternatives then can be examined among the possible variants of physical design. Such a method much increases the likelihood that a "best" system will be arrived at. In this case it would be a system which would provide the proper balance of regulation and other facilities to supply water in the amounts indicated at least cost. Another operations analysis technique which may be used toward the same end is that of the mathematical model, as in quasi-linear programing. (See app. 4.)

The use of consumption models already has been experimented with in the State of New Mexico, with some interesting results.[14] Experiment with simulation techniques has been undertaken by the Corps of Engineers in their recent 308 study of the Columbia, by the International Boundary and Water Commission on the Rio Grande, and by the Harvard Program of Research in Water Resources Development. The use of mathematical models is now under study by the Harvard program.

Operations analysis techniques also should be able to increase the precision of system operations. Here again, the simulation technique and the mathematical model can be used. The first has been applied in electric power system analyses by the Tennessee Valley Authority, the Bonneville Power Administration, and by private electric utilities. The Corps of Engineers has experimented with the use of a linear programing model for operating the reservoirs of its Missouri River Basin system.

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[14] "Report of the New Mexico Project Committee on the Income and Product Results of Alternative Water Uses." The committee was composed of representatives of the University of New Mexico and various State of New Mexico agencies. The report has been completed and will be published during 1960.

The attractiveness of operations analysis techniques for future system design and operation in water development can best be understood through the key role of the high-speed computer. Both the civil engineer and the economist are freed from the restraints of routine computations. The number of alternatives which they can examine is multiplied many times, each of the alternatives may be examined more precisely, and the engineers especially can devote more time to imaginative planning.

Some of the possibilities of operations analysis have been described in a Rand Corp. study.[15] Probably the most intensive experiment with the application of these methods has been in the Harvard University Program of Research in Water Resources Development, where they have been applied to a hypothetical river system (app. 4). The simulation method also has been used as part of an interesting analysis by Resources for the Future, Inc. of sequence and timing in project planning on the Columbia River.[16] When perfected, the application of these more precise tools of analysis can do much to avoid the confusion and costs which may have attended the simple addition of fragmentary economics and good engineering in the past.

Prognostic hydrology

The design of every water resource facility to a certain extent is dependent upon hydrologic projections or forecasts. It is also apparent that many water management operations may be influenced, some vitally, by the accuracy of projections of water receipts and runoff within a basin. Projections are particularly important for the design and operation of systems of water regulation and flood control facilities. For all but a few planning purposes, hydrologic projections for design and operation now are made largely on the historical records of streamflow. These projections are not adequate and experiment toward their improvement is very much in order.

Like overall weather forecasting, hydrologic forecasting may be divided into the short-range and the long-range aspects, although the parallel to weather forecasting is not exact. Short-range forecasts[17] have been given considerable attention, and to some extent are a part of management in most systems of water storage and release. However, long-range projections or forecasting has been less fully studied, and potentially can be of great value in both design and operation. The problem is illustrated in figure 5 ("Drought Periods").

It is here suggested that an important new set of techniques may be described under what we shall term prognostic hydrology. These include: (1) the application of heretofore unused statistical techniques to the actual hydrologic record, so as to improve interpretations of that record, or projections; and (2) the development of new bases for prediction. Among the applications of statistical techniques, experiment with synthetic hydrology,[18] probability analysis,[19] and other analytical tools already have produced promising results. However, it must be stressed that some of the most important advances in this area will depend upon fundamental research in dynamic meteorology and in knowledge of the fluctuations of radiation receipts and their physics on the earth's surface. Hence, it is from new bases of prediction that the most influential long-range results are to be expected.

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[15] Roland N. McKean, "Efficiency in Government Through Systems Analysis—With Emphasis on Water Resources Development," a Rand Corp. research study, John Wiley & Sons, New York, 1958.

[16] John S. Krutilla, "Sequence and Timing in River Basin Development With a Special Application to Canadian-United States Columbia River Basin Planning," Resources for the Future, Inc., Washington, 1960. Pp. 21–26, 32–35.

[17] Short-range forecasts here are interpreted to mean anything from diurnal to seasonal range; long range, on the other hand, is concerned with the fluctuations in maximums-minimums and means of annual water receipts and runoff.

[18] See app. 5. Snythetic hydrology generates streamflow data by application of statistical techniques. For example, mean monthly flows of record may be serially correlated so as to derive a systematic base. Appropriate random components may be applied to the base to generate synthetic monthly flows, which may provide the construction planner with a more useful projection of hydrology than an actual historical series.

[19] See Luna B. Leopold, "Probability Analysis Applied to a Water-Supply Problem," U.S. Geological Survey Circular 410, Washington, D.C., and Walter D. Langbein, "Water Yield and Reservoir Storage in the United States," U.S. Geological Survey Circular 409, Washington, D.C., 1959. Leopold notes that there is a difference between a forecast and probability analysis. The latter uses an actual record as an indication only of the probability of events occurring in the future, not as exact forecast. In the absence of a basis for a true forecast, like synthetic hydrology, it can facilitate the construction of a much better prognosis of hydrologic events than a simple projection of past records.

One well-known student of the sun has testified that the study of solar changes and their correlation with the general circulation of the earth's atmosphere show promising clues toward explaining rainfall fluctuation in Western United States.[20] Other scientists are more hesitant about predicting results, but all agree that study of the earth's incoming and outgoing energy is vital to attack upon the most basic questions of hydrometeorology. It is important, therefore, that the unity of widely varying research activities must be kept in mind as part of a subject having a single and potentially most influential objective. These may extend from observation of solar magnetic fields to the electrical attributes of a raindrop, and mathematical models of the general atmospheric circulation.

New techniques of physical design and construction

There is no doubt that developments favoring still further economies in the costs of storage and other water system facilities will be achieved in the future. These may come either through (*a*) new concepts of structural design; or (*b*) new and more efficient applications of energy, labor and materials to engineering problems. The first is illustrated by recent innovations in European hydraulic structures where competitive designing has resulted in some daring concepts which achieved substantial economies of materials over traditional designs.[21] The particular subject of materials economy, as well as the economies to be achieved from standardization of components has not yet received the attention in American hydraulic designing practice that they might. Some opportunity in this direction thus lies open for the future.

New applications of energy and materials already have had a profound influence on the construction of water control systems, particularly in the introduction and perfection of heavy earth-moving equipment, improved concrete mixing equipment, and long-distance conveyor belt haulage of construction materials.

The next potential or revolutionary techniques of this class would appear to be related to the use of nuclear explosives. Knowledge of radiation effects and their control at present are incomplete so that no firm forecast of the future use of nuclear explosives can be made. However, their theoretical potentialities for large-scale earth and rock movements at very low cost are so great that long-range planning for water policy must contemplate them. The possibility of considerably altered engineering approaches to problems of storage, particularly underground storage, should certainly be entertained in policy planning. (See appendix 10.)

EXPLORATION FOR, DISCOVERY, AND EXPLOITATION OF NEW SUPPLIES

It is obvious that a first line of approach to the problem of meeting water requirements will always be the exploitation of a new supply, where it is obtainable, rather than the application of restrictions in use or compromises on water quality. Where possible in the future these new sources will be sought in the traditional surface supplies. However, it is already apparent that new types of source would be welcome even now in large sections of the country and they may be essential in still larger areas during future years. Such sources may be sought either in the atmosphere or underground. The sea also may reasonably be considered a new source, but it is considered here in the later paragraphs on the waters of substandard quality.

The art of weather modification is still so near its beginning that the full extent of its future impact upon water supply techniques is not presently evaluable. Enough is known, however, to enter weather modification as a source of water in the Western States of at least modest potential. On the basis of the conclusions of the Advisory Committee on Weather Control it would seem reasonable to plan on the eventual addition of approximately 15 million acre-feet annually to western water supplies from this source (table 5). This would not be a major factor in the design or operation of systems of multiple-purpose works in the region.[22] The final answers on weather modification, however, are in the future—perhaps many years in the future—after the completion of a great deal of painstaking fundamental research. The more revolutionary impacts of

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[20] Walter O. Roberts, "Recurring Droughts—A National Problem," testimony before U.S. Senate Select Committee on National Water Resources, Denver, Colo., Nov. 20, 1959 (release, dittoed, 14 pp.).

[21] The 1959 failure of the Malpasset Dam in southern France, however, has reinforced a conservative hesitation to adopt such design techniques, even though the cause of the failure was officially ascribed to unusual weathering of anchoring rock formations.

[22] See Ackerman and Löf, op. cit., pp. 377-378.

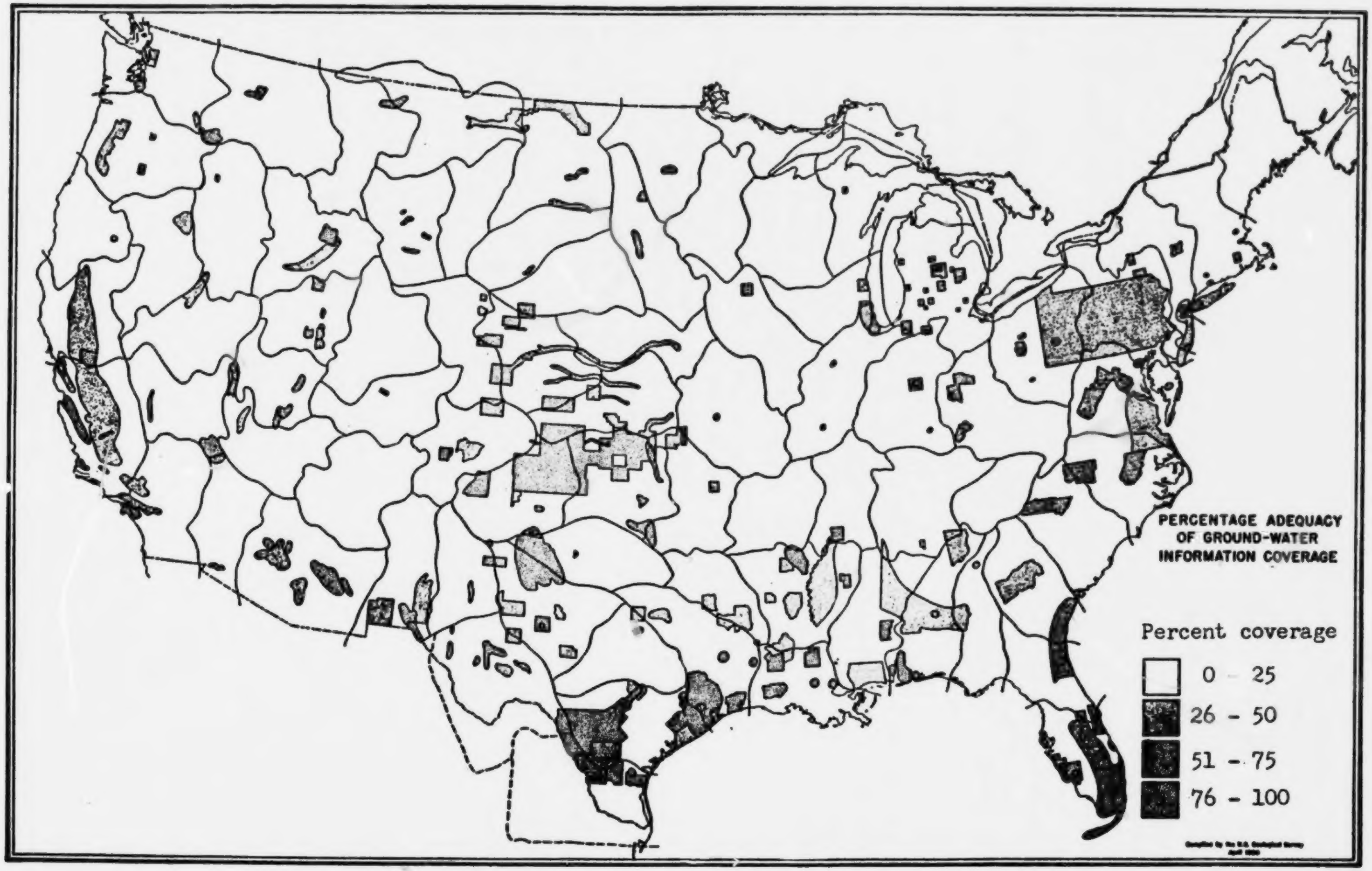
PERCENTAGE ADEQUACY OF GROUND-WATER INFORMATION COVERAGE
Percent coverage
0 - 25
26 - 50
51 - 75
76 - 100

FIGURE 4.—Percentage adequacy of ground-water information, United States. Patterns show present status of available ground-water data, in percentage of complete coverage, based chiefly on published U.S. Geological Survey studies. Complete coverage allows development of large-scale, long-term ground water projects without further investigation. Only a single part of the country is included in this category. (From Walter B. Langbein and William G. Hoyt, "Water Facts for the Nation's Future—Uses and Benefits and Hydrologic Data Programs", The Ronald Press Co., 1959, pp. 26–27).

weather modification on water supply still retain enough probability to warrant not only careful attention in research but also continuous monitoring in water development planning. Runoff from weather modification promises the cheapest additional water to be obtained in the future.

An early need in determining final policy is an exploratory study of the economics of weather modification to assist decisions on the amount and kind of effort which publicly should be placed in this field (appendix 6).

The other major source of new supply will be the aquifers which lie beneath the surface. In the past we have been handicapped by the limited means which we have had for discovering aquifers and appraising their productiveness. Some change in the situation has come from the development of sensitive geophysical instruments and means of interpreting the water content of underground structures.[23] The perfection of these means and their application in a large-scale program of exploration in the Western States (see fig. 4) must be counted upon as one of the technical events of the future.

TABLE 5.—*Estimate of potential precipitation increases by artificial cloud seeding in Western States*

State	Total area (acres)	Annual precipitation (inches)	Estimated part of annual precipitation from orographic clouds (percent)	Estimated possible maximum increase in precipitation by artificial seeding		Estimated possible maximum increase in runoff by artificial seeding [1]	
				Inches	Thousand acre-feet	Inches	Thousand acre-feet
Arizona	72,901,760	12.5	20	0.3	2,300	0.02	100
California	101,563,520	20.9	50	1.0	8,500	.4	3,400
Colorado	66,724,480	16.5	40	.7	3,900	.2	1,100
Idaho	53,476,480	17.2	60	1.0	4,500	.5	2,200
Montana	94,168,320	14.8	30	.4	3,100	.1	800
Nevada	70,745,600	8.6	20	.2	1,200	.02	100
New Mexico	77,866,240	14.3	20	.3	1,900	.02	100
Oregon	62,067,840	27.8	40	1.1	5,700	.6	3,100
Utah	54,346,624	13.2	30	.4	1,800	.05	200
Washington	43,642,880	32.0	50	1.6	5,700	1.0	3,600
Wyoming	62,664,960	14.6	30	.4	2,100	.1	500
Total	760,168,704				40,700		15,200
Total 5 Pacific Coast and Rocky Mountain States [2]							13,400
Percentage in 5 States							88

[1] Computed by use of natural ratio of runoff to precipitation.
[2] Washington, Oregon, California, Idaho, and Colorado.

Source: Ackerman and Löf, op. cit., table 30, p. 375.

The extent to which these supplies are exploited, particularly below the present critical level for water lifting of about 1,000 feet, will depend upon three things: (*a*) the public attitude of the affected States or regions toward ground water withdrawal which exceeds aquifer recharge, (*b*) the mechanical efficiency of lifting devices and the costs of energy which these devices must depend upon, and (*c*) the costs of locating and appraising aquifers, and drilling wells to them. All three aspects—appraisal, improvement of lifting devices, and energy costs for ground water exploitation—appropriately should enter public policy consideration insofar as it is mindful of the future of the West. Important eastern aquifers, like those of the Atlantic and Gulf coastal plains, should not be forgotten in the appraisal.

The possibility that full knowledge of the extent and the movement of underground waters may weaken our attachments to watersheds and river basins as units for development must be entertained. The water development of the future will be able to consider the integration of surface and ground waters in management plans as well as the integration of related watersheds. As techniques of underground storage are improved, such integration increasingly will become important. Thus in the West particularly we may look forward to the day when water management may be integrated in varying degrees on a "three-dimensional" basis, including atmospheric and underground sources as well as the surface waters under one plan of supply.[24] It has been noted that the present ratio between surface and underground sources of water withdrawn in the United States is about 4 to 1. The forecast has been made that this ratio will change to something between 2 to 1 and 1 to 1 for a country like the United States sometime during the next 20 to 50 years.[25] Although ground water supplies as compared to surface supplies have the disadvantages of higher costs, service to a limited number of purposes, and frequently higher dissolved solids content, they also have some outstanding advantages. These include their wide dispersal within a region, lack of evaporation loss, lower temperatures, lesser fluctuation, and natural protection against radioactive contamination or other military action.[26] Recognition of these characteristics along with more methodical application of the techniques of discovery and appraisal in the future is likely to become a familiar part of water management which goes beyond integrated multiple-purpose river basin management.[27]

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[23] See Ackerman and Löf, op. cit., pp. 384-406.

[24] Integrated management of ground and surface waters already is practiced in parts of the West, as in the Roswell basins of New Mexico.

MEASURES FOR CONSERVATION AND REDUCTION OF DEMAND

In situations where new supplies fail to meet requirements or where additions of physically available supply are impractically expensive, water management can turn from the engineering of supply to the engineering of demand. The old British maxim "a penny saved is a penny got" has a parallel in water development, for the drops of water saved certainly are drops available.

A variety of measures are available and are likely to be considered a part of future water management which might be classified as means of engineering water demand. One simple and effective means of conservation which awaits adoption in many localities is metering. Other pertinent techniques are recycling, water-conserving agronomy, forest and range management for water yield, evaporation suppression, and planned location of demand through controlled land use.

There are three aspects to the possible reduction of demand for water or water services: the reduction of requirements for withdrawal of water; the reduction of consumptive depletion or disappearance; and the reduction of demand for noncomsumptive water development purposes, like flood control. For the first, by far the most important technique of the future is likely to be recycling, or the intraplant reuse of water for manufacturing purposes.

Recycling

Every indication of trend suggests that manufacturing use will be the most rapidly growing of the requirements for water withdrawal in the future, and recycling already has been proven a potent means of reducing requirements in the face of local or regional water scarcities. In the future it can be a most influential means of regulating withdrawal requirements where there are scarcities of supply, or where thermal pollution is considered a harmful condition. Recycling can reduce fresh-water requirements to a small fraction of normal once-through use. It has been estimated that a severalfold increase in the Nation's industrial output is possible at little or no increase in its total fresh-water demand, mainly because of recycling.[28] It should be noted, however, that the techniques of recycling are not likely to effect much reduction in consumptive depletion or water disappearance; their effects are limited principally to the withdrawal requirements. The principal cause of water disappearance during industrial use is evaporation to transfer to the atmosphere heat absorbed by cooling water in steam-electric plant condensers, and manufactural processes. The amount of water evaporating may be expected to be approximately the same whether recycling is used or "once-through" water is released to streams or other natural water bodies.

Vegetational management for water yield

The techniques most likely to alter favorably water disappearance or consumptive depletion are those concerned with vegetation. The reduction of water requirements through forest and range management practices and through water conserving agronomy does not have the same potentiality for reducing withdrawal requirement as recycling, but it appears to be the direction in which to look for any major change in water disappearance. Already the reduction of water wastage through phreatophyte control has illustrated some of the possibilities.[29] Experiments which are being conducted now in Arizona may give some more conclusive answers as to the water releasing capacities of forest and range management directed toward water yield. Some of the most difficult questions surrounding these techniques are those of economic evaluation of comparative benefits from different types of management (i.e., forest- or range-intensive management or water-intensive management). Water conserving agronomy also would seem to have possibilities. Much already is known about the adaptation of crops to restraints on water consumption. However, the theoretical potentialities that accompany plant physiology and plant genetics research alone make water conserving agronomy worthy of inclusion in water management now.[30] In addition, there are already proven techniques of water budgeting in irrigation practice which deserve wider consideration than they have had (app. 8). Finally, the further study of soil moisture, vegetation relations, and the connection of ground water manipulation with them holds promise of increasing water yield through vegetative management.

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[25] Alfred Loehnberg, "Water and Economic Development," Impact of Science on Society, vol. IX, 1958, pp. 23-44.

[26] Loehnberg, op. cit., p. [illegible]

[27] See also app. 7.

[28] Ackerman and Löf, op. cit., p. 441.

Evaporation suppression

Because of the amount of water which can be evaporated from any open surface during the summer season in Western United States, evaporation suppression recently has become an enticing subject for investigation. The immediate goal is the development of economical methods capable of saving the 10 million-plus acre-feet of water estimated to be evaporated annually from reservoir surfaces in Western United States.[31] Under certain conditions, as for treated water in municipal supply systems, physical coverage of storage facilities is economically justified to prevent evaporation. In other cases advantageous location of reservoirs so that there is a low ratio of exposed surface to volume may reduce evaporation loss considerably. The most favorable location, of course, is underground storage, and evaporation suppression certainly is one reason for attention to underground storage in the future. However, storage with extensive exposed surfaces almost inevitably will continue to be a part of stream regulation. Because physical coverage of such surfaces is prohibitively expensive, recent investigation has concentrated on the monomolecular chemical films which have shown promising results on small reservoirs.

The importance of evaporation control studies extends much beyond the immediate goal, attempting to save a substantial part of the conjectured 10 million acre-feet now lost. In his study of water yield and reservoir storage, Langbein has suggested that there are definite practical limits to the use of storage for regulation of any given streamflow.[32] Evaporation loss from reservoir surfaces is one of the factors, particularly in Western United States, diminishing the effects of storage upon regulation for all surface storage increments beyond a certain regulation-flow ratio.[33] Successful suppression of evaporation could alter the basic relation between storage and flow determined by Langbein, and therefore the completeness of regulation that would be economically feasible for a given stream. The less evaporation from storage is, other things being equal, the longer the period of flow which can be regulated. Where significant flow fluctuations occur over a number of years, as in Western United States and other arid and semiarid environments, this has substantial practical significance. For example, if reservoir evaporation on Colorado River storage systems of the sizes described by Langbein were reduced by 50 percent, the reservoir capacity at which maximum regulation is reached is 78 million acre-feet rather than 52 million acre-feet, as under estimated natural evaporation. Where added storage becomes feasible, all flow and consumptive uses benefit. Hydroelectric generation is increased in proportion to the added volume of water available; and irrigation, industrial, and municipal use gains similarly.[34]

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[29] Phreatophytes are water-loving plants like the salt cedar which grow on the edge of water courses or on reservoir borders. See Department of the Interior, "Report on Phreatophytes" prepared for the Senate Select Committee on National Water Resources, Washington, D.C., December 1959, 31 pp.

[30] See the following references for treatment of vegetation-water yield relations: Edward A. Colman, "Vegetation and Watershed Management; An appraisal of vegetation management in relation to water supply, flood control, and soil erosion." The Ronald Press, New York (1953), especially pp. 129-142.

Leon Lassen, Howard W. Lull, and Bernard Frank, "Some Fundamental Plant-Soil-Water Relations in Watershed Management," U.S. Department of Agriculture Circular No. 910, Washington, D.C. (1952).

Paul R. Nixon, "Water Yield Predictions Based on Watershed Characteristics," Iowa Agricultural Experimental Station Journal Paper No. J-2969, Ames, Iowa (1956).

For an interim report on the Arizona program see: Arizona Watershed Program, "Recovering Rainfall," Tucson, (1956).

[31] See E. D. Eaton, "Control of Evaporation Losses," memorandum of the chairman to members of the Senate Committee on Interior and Insular Affairs, Apr. 14, 1958 (Washington: U.S. Government Printing Office); also Ackerman and Löf, lp. cit., pp. 451-457. Estimates vary over a wide range and basic data are meager. The Bureau of Reclamation estimates that 2,000,000 acre-feet annually might be saved by 1980 in the Western States by monolayer use. U.S. Department of the Interior, Bureau of Reclamation, "Measures for Minimizing Water Storage and Conveyance Losses in the 17 Western States," Denver, Colo. (1969), p. 7.

[32] Langbein "Water Yield and Reservoir Storage in the United States," U.S. Geological Survey Circular 409, as previously cited.

[33] Ibid., p. 4.

An interesting special application of evaporation suppression techniques could occur where moderately saline lakes exist. If the evaporation-inflow ratio were reduced, water of these lakes might become usable.

To realize such possibilities, however, fundamental research and continued experiment may be necessary for a long period. Present evaporation suppression methods, while promising for small water bodies, do not appear to have the capacity for general application needed for major effect upon feasible storage-flow ratio in river basin development. The value of subsurface water storage where physically possible, should be considered in this connection.

Location of demand by planning land use

Each of the techniques discussed in this section in some way has touched upon a process which we might call the engineering of demand. Thus, recycling is designed to increase the units of output in a manufacturing plant for the unit of water withdrawn or consumed. Water conserving agronomy may seek to maximize the financial returns to the farmer per unit of water used through selection of crop plants, carefully determined means of application, and other measures. Forest and range management for water yield should seek to maximize the economic return from the water that falls within a given watershed by management which takes account of municipal, industrial, and irrigational uses of water. Evaporation suppression is directed toward a reduction of the water consumed in the operation of facilities for flow regulation. A final and potentially powerful measure is the planning of land use in such a manner that location of demand for water facilities will be compatible with efficient development.

There is nothing unprecedented or novel in the idea of planned land use. Perhaps its most familiar form is urban area zoning, but zoning of rural land use also has occurred, as among the nonagricultural counties of the lake States during the 1930's.[35] These zoning regulations, in effect, were public decisions upon the location of demand for public services in sparsely settled, low-income areas. Generally, many important decisions of this kind usually have been initiated from private sources, as in the location of a residential subdivision in a metropolitan area. Zoning or other measures toward forming and enforcing a public decision about land use have been used relatively little in water development. The relatively few cases of application have concerned principally flood control; indeed, it is for the function of flood-damage prevention that the first really vital need for publicly controlled land use is being felt in water development.

Gilbert White has aptly summarized the situation which has caused the Nation to commence recognizing planned land use as an important adjunct technique in water development. He has stated—

> * * * although there have been remarkable engineering achievements over the period of 22 years since the first national flood control act passed, flood damage has continued to mount. The occupance of flood plains has continued to spread * * *. It is a hard fact that the traditional approach to flood control through engineering works alone has not achieved the reduction in the annual bill the Nation is paying in flood losses. Major reductions had been anticipated 22 years ago when engineering efforts were launched outside of the lower Mississippi and Sacramento Valleys. It is a losing battle in some areas, and it is one which cannot be won simply by redoubling the investment in dams, levees, and channel improvements * * *.

Moreover, there are areas where no engineering works can be justified. In many such areas, as well as along

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[34] The effects of evaporation suppression upon storage and regulation also might be interpreted from another point of view. Thus Louis Koenig has noted that the amount of regulation provided under existing evaporation conditions could be given by a much smaller reservoir capacity, and smaller capital expenditure, assuming a 50-percent reduction in evaporation. For example, a 50-percent reduction on 1959 Colorado reservoirs would increase annual regulation by 400,000 acre-feet (Louis Koenig, informal report to Walter B. Langbein, undated).

[35] Erling Day Solberg, "Rural Zoning in the United States," U.S. Department of Agriculture, Information Bulletin 59, Washington, D.C., U.S. Government Printing Office (1952).

> some streams where reservoirs have been constructed, there is continued construction of new buildings within the reach of floods. It is not enough to say, "No further work warranted."[36]

These facts and others have stimulated some careful examination of the possibilities of planning land use for flood-damage prevention within the last few years. Metropolitan or urban agencies in a number of cases have developed urban renewal plans with reduced flood-damage potentials.[37] Federal agencies like the Tennessee Valley Authority, the Corps of Engineers, and the U.S. Geological Survey have commenced studies to provide technical information, like flood hazard estimates, which later can assist the development and application of this technique.[38] States like the Commonwealth of Pennsylvania and the State of Tennessee also have undertaken some preparatory work.

Although care will have to be taken in the application of public land use control for flood-damage prevention so as not to foreclose upon high value occupance where it is warranted, the field for application of these techniques in flood-damage prevention is so wide and their contribution to efficiency in water development of such high potential that they appear certain to be a part of future public planning.

The outlook which has been opened in flood-damage prevention raises questions as to the potential application of planned land use to other aspects of demand for water facilities. It is obvious that planning practices which determine the location and density of urban settlement also can influence the location of requirements for domestic water supply and for investment in facilities developing that supply. An interesting and virtually unexplored area in thought about these techniques concerns industrial location. Although many other factors in addition to water availability must be considered in the location of new manufacturing plants, it is obvious that future water demands, and therefore demands for publicly financed water facilities, will be influenced by decisions on industrial location. The extent and degree to which the public should share in these decisions may demand future attention; accordingly, preparatory examination of the possibilities would seem a prudent part of policy. The sort of problem which will have to be considered is clearly indicated by the statement of a prominent Colorado scientist to the select committee:

> * * * we should take cognizance that population growth is now very great in regions where the peril of severe drought is highest. This implies, particularly, that it is only sound judgment to deflect away from drought-prone areas those industrial developments that use large amounts of water.[39]

This question in the future will be of particular importance where pressures for interbasin diversions exist or can be foreseen. Examination of planned land use as a measure for introducing efficiency of development within a given basin also has potentialities and needs study.

TREATMENT AND USE OF WATERS HAVING SUBSTANDARD QUALITY

A drought may be created or it may exist because of the presence of unusable waters no less than by the physical absence of water. This is a fact upon which poignant testimony was provided by many early settlers in western United States who found water supplies with too high a salt content for domestic, irrigation, or livestock use. It is a fact which also may be attested to by many more recent well-drillers in sections of the Great Plains running from the Canadian border to that of Mexico. Moreover, it is a type of drought to which no part of the country is immune, not even humid areas. As the density of settlement in the country has increased and industrial growth proceeded, we have turned many naturally usable supplies of water into an unusable state by pollution and contamination. This may come through disposal of bacterial and other untreated organic wastes, disposal of inorganic chemical wastes, increasing stream sediment loads, and through salt water encroachment in mined aquifers. A potentially powerful and potentially pervasive new pollutant also must now be contemplated.

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[36] Gilbert F. White, "Action Program for the States: A New Attack on Flood Losses," "State Government," [published by] the Council of State Governments, Chicago, spring 1959 (reprint, pp. 1, 2). See also Gilbert F. White et al., "Changes in Urban Occupance of Flood Plains in the United States," University of Chicago, Department of Geography, Research Paper No. 57, 1958.

[37] White, "A New Attack on Flood Losses," p. 2.

[38] Tennessee Valley Authority, "Program for Reducing the National Flood Damage Potential," 1959, and idem, "Flood Problems and Management in the Tennessee River Basin," 1959. See also U.S. Geological Survey, "Hydrologic Investigations Atlas," e.g., "Floods at Topeka, Kans.," HA-14, Washington, D.C., 1959.

[39] Walter O. Roberts, "Recurring Droughts—A National Problem," testimony before the Senate Select Committee on National Water Resources, Denver, Colo., Nov. 20, 1959, transcript, p. 14.

This is pollution by radioactive wastes. The possibility that man-made "drought" may occur within localities or regions of the future United States must be entertained as the density of settlement increases and as our capacities for polluting or contaminating water also increase. It can affect all withdrawal uses and recreation.

However, the droughts created by man's contamination or by the substandard quality of naturally occurring waters are less harsh over the long term than the droughts created by lack of precipitation. There are within our means methods for avoiding contamination, reclaiming polluted and other substandard waters, and adjusting use to a variety of quality requirements.

Today nearly all water supplied by municipalities, much of that withdrawn for industrial use, and even some irrigation waters are treated before use. A number of practices have been developed to improve the quality of water. It can be mechanically processed by filtration, aeration, or sedimentation, and it can be treated chemically in many ways. Today practical means exist to remove calcium and magnesium salts present in water as bicarbonates, chlorides, sulfates, or nitrates, iron compounds, sodium compounds, and other inorganic materials which may be present in water solution. Nearly all undesirable microorganisms which can live in water can also be destroyed and means exist for the elimination or neutralization of most wastes which can be waterborne. As is now well know, even sea water can be desalted and the product made available for consumptive uses which can support high costs.

Means thus already have been recognized and applied to the treatment of waters with substandard quality. However, there are three problems which they present for future policy and future management: (1) lowering the cost of treatment; in some cases the objective must be lowering to levels considerably below the known most economical means of the present; (2) the development of methods of coping with new pollutants of innovational nature; (3) recognition that these techniques are effective tools for increasing the availability of water, and can be a part of comprehensive management.

The question of economical means of treatment

As already suggested, there is a great variety of water treatment processes already applied to the remedy of undesirable water conditions of different kinds. Some are applied on a very wide scale, like the treatment of organic wastes. Nonetheless, they all fall short of the truly effective contribution to water availability which may be considered desirable. For example, processes for treating organic wastes (like ordinary sewage) are familiar and relatively simple. Yet there are many communities whose citizens believe that their financial resources would be or are severely taxed by treating organic wastes so as to eliminate contamination of water by those wastes. One answer has been to supply Federal or State aid for such communities. While this is entirely commendable from a social point of view, it is at the same time an indication that technology still has opportunity to contribute toward a lasting answer to the problem of treating organic wastes. Such an opportunity lies before technology until the time that any community can treat its wastes without encountering financial difficulties in so doing.

Although the treatment of chemical wastes from industry has advanced enormously in the last 20 years, the problem of costs still appears to be present. Few States or districts which are now attempting to attract new industries tolerate the release of untreated wastes into their waters. However, the problem is still a significant one in many older industrial areas where treatment costs may seem prohibitive to a reluctant management, or on a marginal operation.

Perhaps the most striking area of water quality improvement where costs are critical is in desalting sea water and brackish water. The accelerated experiment now underway in federally supported programs essentially is a search for cost reduction. A number of interesting and ingenious methods of desalting now are under investigation by the Department of the Interior Office of Saline Water and its contractors.[40] As yet, however, no truly low cost process is in sight. Costs in the range

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[40] See Department of the Interior Office of Saline Water Report to the Senate Select Committee on National Water Resources, "Saline Water Conversion."

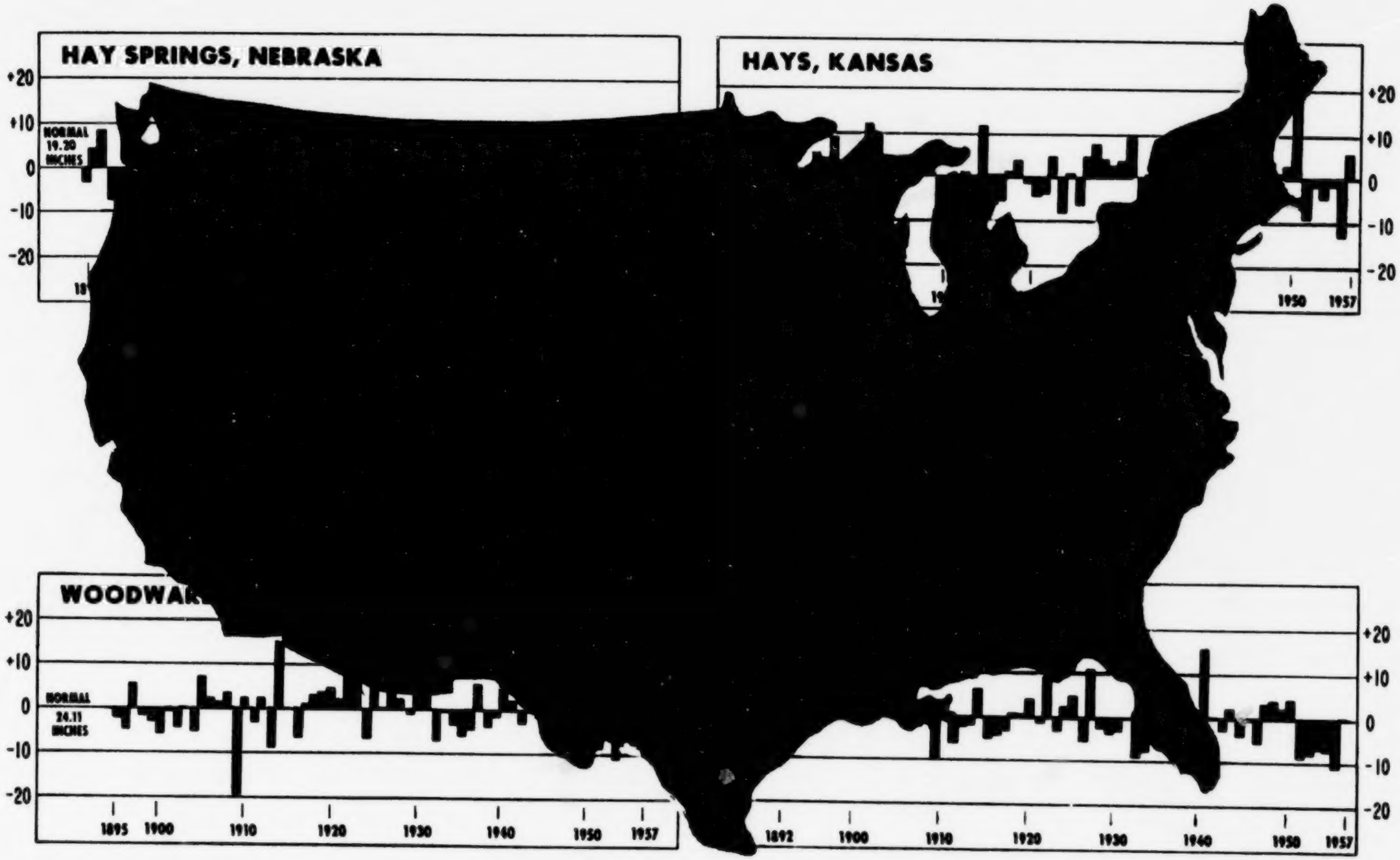

Figure 5.—Great Plains drought periods. (From "A Report on Drought in the Great Plains and Southwest," prepared under the direction of the Special Assistant to the President for Public Works Planning, October 1958.)

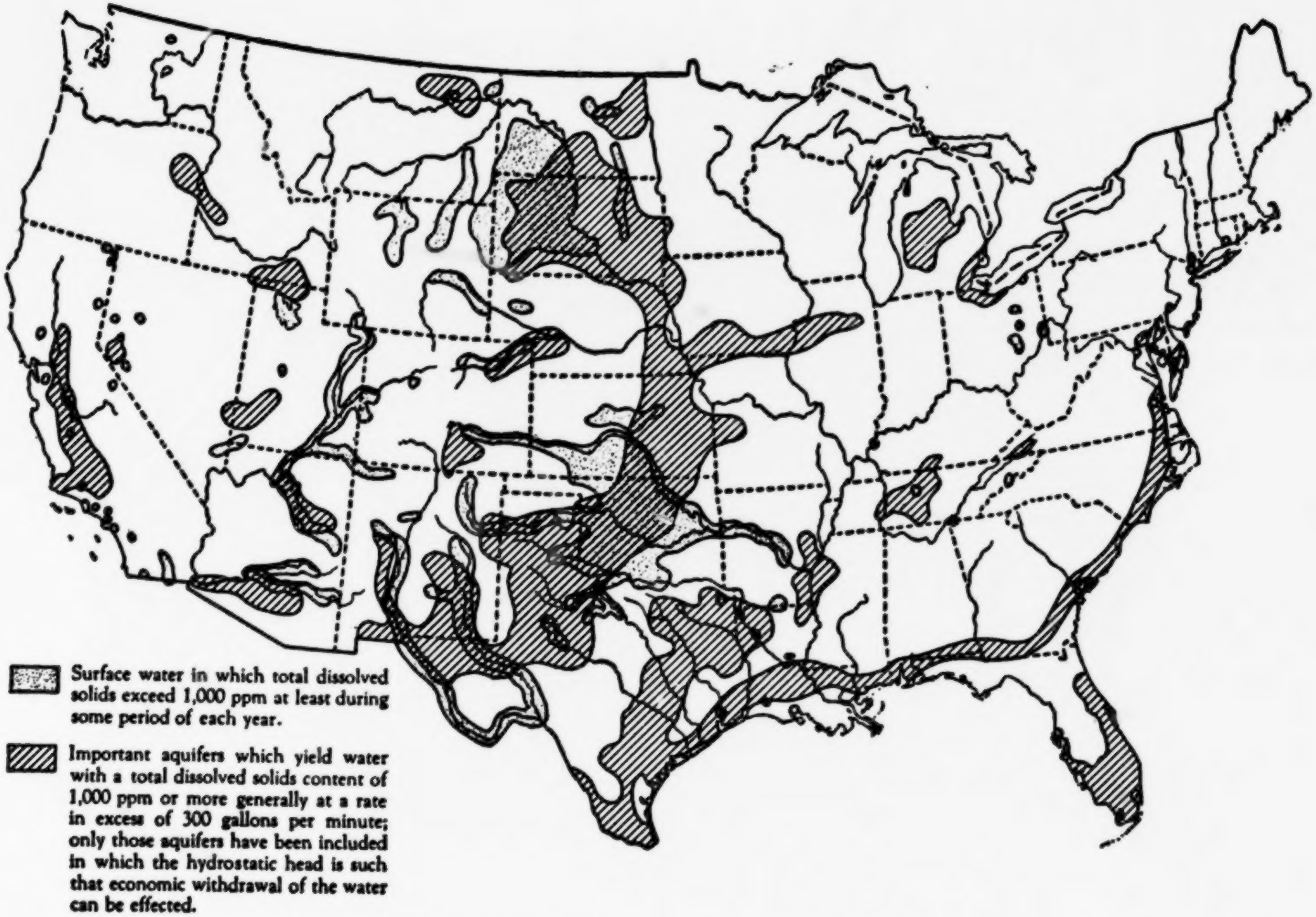
▨ Surface water in which total dissolved solids exceed 1,000 ppm at least during some period of each year.
▨ Important aquifers which yield water with a total dissolved solids content of 1,000 ppm or more generally at a rate in excess of 300 gallons per minute; only those aquifers have been included in which the hydrostatic head is such that economic withdrawal of the water can be effected.

FIGURE 6.—Saline surface and ground water in the United States.

(From U.S. Geological Survey Water Supply Paper 1374, and Ackerman and Löf, op. cit., p. 346.)

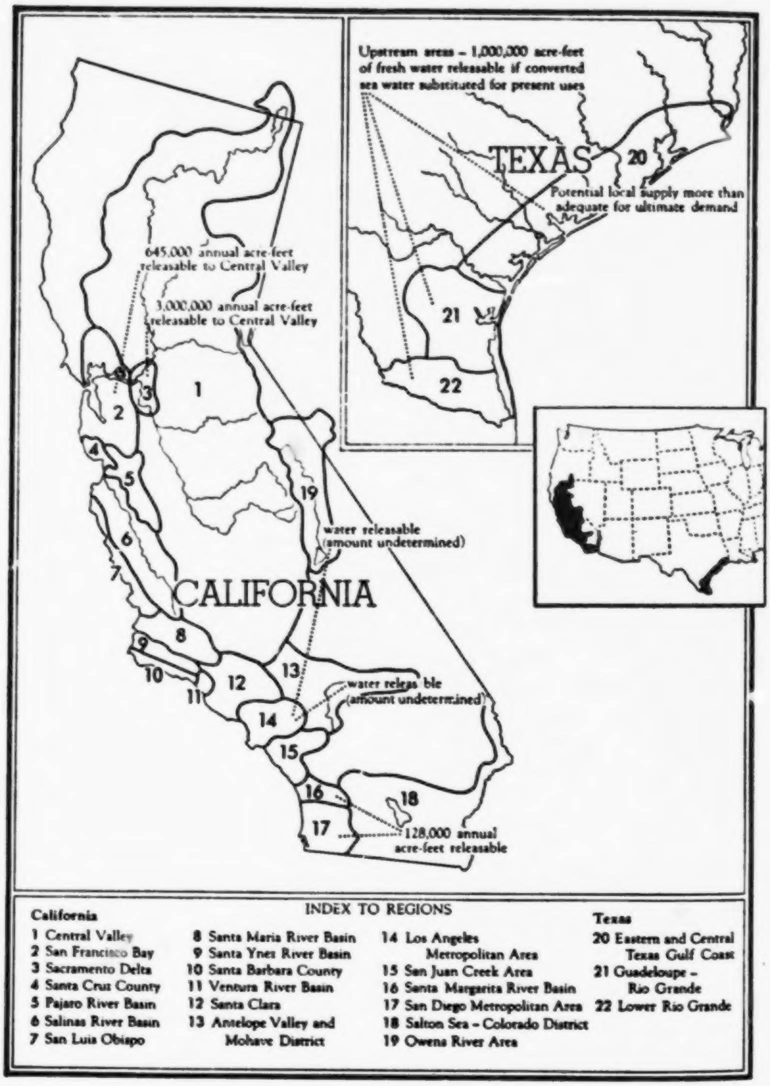
Upstream areas – 1,000,000 acre-feet of fresh water releasable if converted sea water substituted for present uses
TEXAS
20
Potential local supply more than adequate for ultimate demand
21
22
645,000 annual acre-feet releasable to Central Valley
3,000,000 annual acre-feet releasable to Central Valley
1
2
3
4
5
6
7
19
water releasable (amount undetermined)
CALIFORNIA
8
9
10
11
12
13
water releasable (amount undetermined)
14
15
16
17
18
128,000 annual acre-feet releasable
INDEX TO REGIONS
California
1 Central Valley
2 San Francisco Bay
3 Sacramento Delta
4 Santa Cruz County
5 Pajaro River Basin
6 Salinas River Basin
7 San Luis Obispo
8 Santa Maria River Basin
9 Santa Ynez River Basin
10 Santa Barbara County
11 Ventura River Basin
12 Santa Clara
13 Antelope Valley and Mohave District
14 Los Angeles Metropolitan Area
15 San Juan Creek Area
16 Santa Margarita River Basin
17 San Diego Metropolitan Area
18 Salton Sea – Colorado District
19 Owens River Area
Texas
20 Eastern and Central Texas Gulf Coast
21 Guadeloupe – Rio Grande
22 Lower Rio Grande

FIGURE 7.—Regions of potential demand for demineralized sea water for irrigation. The figures in annual acre-feet indicate the approximate amount of fresh water potentially releasable to nearby areas if demineralized sea water were to be fully used in the coastal regions. Economic feasibility of supply was not considered in compilation of the data used on this figure and in table 6. (From U.S. Department of the Interior, Office of Saline Water, "Potential Use of Converted Sea Water for Irrigation in Parts of California and Texas," 1954.)

of 50 cents per thousand gallons ($165 per acre-foot) are contemplated although not yet achieved.[11] If desalted water at 50 cents per thousand gallons becomes available, important effects on local water supply in critical areas are readily apparent. Such water comes within the cost range estimated for some important interbasin diversion projects. For example, a proposed project for bringing additional water to the Nevada desert from the Columbia River, assuming that this were politically feasible, has been estimated to involve total costs of about 40 cents per thousand gallons.[12] Although it is clear that demineralized water at these costs could not be used for irrigation purposes, it presently shows promise of being competitive for industrial and domestic uses in some areas. Although only a few American coastal cities have immediate need for additional water supply, a number of water-scarce inland municipalities are either within feasible pumping distance of sea water or accessible to saline ground water supplies. Coastal sections of California and Texas seem especially interesting in this connection. So do many parts of the Great Plains underlain by saline water-bearing aquifers. (Figures 5, 6, and 7, and table 6.) It must be stressed, however, that any widespread application of desalinization processes will depend on the reduction of total costs of operation to levels not yet achieved, even though such costs are likely to be attained. The critical part of the desalting program thus still centers on cost reduction. Economical reduction of the sodium content of western irrigation water is a special challenge for the future. Every degree of sodium ion reduction in presently employed irrigation waters can reduce water demands for leaching, lessen drainage problems, decrease salt additions to soil, increase crop productivity, and decrease the cost of irrigated farm output in such circumstances. The stakes connected with the desalting program thus are high.

TABLE 6. *Regions of potential demand for demineralized sea water for irrigation*

Region	Feasible pumping elevation for demineralized sea water (feet)	Ultimate deficiency in local supply (annual acre-feet)	Estimated potential market for converted sea water (annual acre-feet)
CALIFORNIA			
1. Central Valley		0	(¹).
2. San Francisco Bay	(²)	1,330,000 to 2,400,000.	1,000,000 to 2,000,000.
3. Sacramento Delta	(²)	0	3,000,000.
4. Santa Cruz County	500	13,000	5,000.
5. Pajaro River Basin		(³)	
6. Salinas River Basin	500	(³)	
7. San Luis Obispo	500	180,000	150,000.
8. Santa Maria River Basin	500	80,000	80,000.
9. Santa Ynez River Basin	500	80,000	60,000.
10. Santa Barbara County	300	70,000	70,000.
11. Ventura River Basin	200	5,000	5,000.
12. Santa Clara River Basin	500	190,000	150,000.
13. Antelope Valley and Mohave District		(⁴)	
14. Los Angeles metropolitan area	2,000	2,100,000	2,100,000.
15. San Juan Creek area	1,000	140,000	135,000.
16. Santa Margarita River Basin	1,000	1,116,000	160,000.
17. San Diego metropolitan area	1,000		728,000.
18. Salton Sea—Colorado District		(⁴)	3,500,000.
19. Owens River area		(⁴)	
TEXAS			
20. Eastern and central Texas gulf coast		0	
21. Guadaloupe—Rio Grande	500	2,880,000	2,880,000.
22. Lower Rio Grande	500	1,650,000	1,650,000.

¹ Undetermined.
² Converted sea water would be usable at lower elevations. Maximum elevation not determined.
³ Currently planned fresh-water developments adequate for anticipated future demand.
⁴ Ultimate deficiency undetermined.

Source: U.S. Department of the Interior, Office of Saline Water, *Potential Use of Converted Sea Water for Irrigation in Parts of California and Texas*, 1954 and Ackerman and Löf, op. cit., table 29, p. 345.

Another field which deserves cultivation but which has not had either the popular appeal or the legislative attention given to desalination concerns the techniques of sediment control. In the economy of this day they have a very wide significance. Reduction or elimination of sediment content has aesthetic, public health, and economic effects which certainly must be considered more heavily in future planning of development. To some development purposes, like domestic, industrial, and municipal water supply, and recreation, sediment control or elimination is absolutely essential. For others like navigation, or power production, it is an economic asset. To meet desirable standards of water quality in the future it is obvious that the cheapest means of sediment control is that of erosion control. It is assumed that their value now so widely recognized will be continued to be applied as needed. However, there are limits to the practical extent of applying measures of erosion control for sediment reduction. One need only consider many local situations in semiarid and arid Western United States to understand this. While natural deposition ultimately takes care of the problem there are situations in which this too is costly or impractical. There is certainly a field for study of possibilities of cost reduction in reducing or eliminating the sediment content of water supplies.

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[11] See Ackerman and Löf, op. cit., pp. 348-349; U.S. Atomic Energy Commission Report to the Senate Select Committee on National Water Resources, "Application and Effects of Nuclear Energy," Select Committee on National Water Resources Committee Print No. 27, Washington, D.C., 1960.

[12] K. C. D. Hickman, "The Water Conversion Problem," Industrial and Engineering Chemistry, 48 (April 1956), pp. 7A-20A, reference on p. 18A. This calculation includes amortization of investment and estimated electricity costs for pumping of about 5 mills per kilowatt hour. See also Appendix 11.

Problems presented by new types of wastes

The many benefits conferred by the application of modern chemistry, and, now, modern physics, upon our means of agricultural and industrial production and upon our domestic pursuits are often accompanied by problems of public safety or convenience. Every existing pollution problem from industrial sources is witness to this fact. These problems may be expected to continue their emergence in the future. One of them, the risk of contamination from the use of radioactive materials, is so spectacular that public interest has stimulated a large and apparently entirely adequate program for developing radioactive waste disposal techniques.[43] However, problems are appearing from less spectacular sources which also deserve methodical attention.

Our increasing realization that many modern chemicals may have subtle but nonetheless harmful physiological effects underlines the need of keeping the chemical waste contamination of water prominently in review. For example, there are no satisfactory means for removing detergents from domestic water supplies; and the use of insecticides and weed killers can produce detectable residues in some water supplies. While we may assume that the effects of these residues are physiologically harmless, recent history in the United States is studded with the discovery of danger in substances hitherto carelessly assumed to be safe. The problem of chemical waste removal therefore may be considered a dynamic one in which public responsibilities are not to be discharged alone by attention to the spectacular or by waiting for the appearance of crises.

Recognition of treatment techniques as a part of water development

There is certainly some appreciation of the potentiality of treatment techniques in water development, and active interest expressed from a variety of sources within the country. Although the Federal Government has shown leadership in some important fields, as in radioactive waste disposal, desalting, and some aspects of organic waste treatment, there is still a degree of reliance on technical leadership at a more local level. This seems to be the case for at least some important problems of chemical waste treatment, and some of organic waste treatment. Moreover, the Federal programs and the existing programs at State and local levels have an isolated individual orientation. They are not yet considered as related to each other or as a part of a whole set of techniques, including multiple-purpose development, whose joint consideration can greatly increase the efficiency and rate of progress in national development. Improved means of weighing the adequacy of current research, development, and application would seem a very natural result from a more comprehensive review.

Use priorities corresponding to water quality

Water uses have differing degrees of tolerance to specific water qualities. Some industrial uses, for example, require very nearly pure or salt-free and sediment-free water. On the other hand, irrigation water may have a high turbidity and a salt content as high as 3,500 p.p.m. and still remain useful in some special situations.

Where treating water of substandard quality is temporarily or permanently impossible, it is therefore apparent that the cause of efficiency in water use may be served by "pairing" of tolerant uses and low quality supplies. This long has been practiced in agriculture, where salt-tolerant crops and salt-tolerant animals like sheep have been employed to make use of water supplies with relatively high salt content. For many years certain coastal industrial plants also have used sea water, principally for cooling purposes. Until recently such use has been deterred by the corrosive action of sea water on metal surfaces and the fouling of heat transfer equipment by precipitated salts and marine organisms. However, improvement in corrosion-resistant alloys in recent years has led to a lessening of corrosion problems in sea water use, making the employment of sea water cooling much more feasible than it has been. As a result, clean sea water now is a generally cheaper and more satisfactory coolant than the contaminated fresh water requiring considerable pretreatment.[44] Besides cooling, sea or other salt waters have other industrial uses, such as flushing or washing operations, sluicing ash, movement of logs and wood chips in pulp mills, laundering and other functions. While decisions on the pairing of use and quality of supply should be and will be made on an economic basis, it is evident that this tool for achieving some efficiencies in water use now is practical enough to be entertained as an alternative to treatment or other means of providing an adequate supply under some local conditions.

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[43] The program of the Atomic Energy Commission and the projects of its contractors. This is not intended to suggest that satisfactory and tested solutions to the problems of disposal which can be foreseen now exist. However, there is an existing establishment with apparent competence for developing such solutions.

IV. THE ORGANIZATION OF DEVELOPMENT

In this report we previously have given a general description of the nature of development and the present major approach of integrated multiple-purpose management, an analysis of the future needs for efficiency in the U.S. water development, and a review of the techniques which can be applied where efficiency is sought. Full understanding of the policy implications of these techniques may be aided by a brief description of the general procedure of development and how it is organized administratively. Under whatever auspices, effort toward development generally follows a procedure which may be described in three major steps: planning for development, realizing development, and operational management.

These three major steps may be described in outline form somewhat as follows:

(1) Planning:

(*a*) Supplying initiative toward the recognition of development problems.

(*b*) Policy formulation. Provision of specific interpretation of general statutes, or necessary legislative modification thereof.

(*c*) Applying all types of research techniques to the clarification and solution of development problems, e.g., planning analysis, programing, etc.

(*d*) Evaluating engineering and economic feasibility of development; physical planning of development; coordination of planning for several purposes of development.

(*e*) Project scheduling.

(*f*) Review of experience and evaluation of progress. Drafting of measures for necessary administrative or procedural reorganization or correction.

(2) Realizing development:

(*a*) Securing or supplying entrepreneurship for development and later operational management.

(*b*) Securing necessary legal authorizations for development and subsequent operation of facilities.

(*c*) Securing or supplying financing; administering disbursement of investment funds.

(*d*) Detailed designing and engineering of projects.

(*e*) Management and supervision of construction or other developmental activities.

(3) Operational management:

(*a*) Necessary physical and mechanical operations.

(*b*) Sale of vendible products or services.

(*c*) Provision of debt repayment.

(*d*) Coordination of all operations with other public or private operations having impinging areas of interest.

These functions generally are pertinent whatever the group or jurisdiction concerned, whether it is the Nation, a group of States, a single State, a district, or a community.

Each of these major steps in the past has brought forth some characteristic problems for public policy and practice which are now familiar to all who are concerned with public or private participation in water development. For example, the identification and the preservation of reservoir sites have been problems of public concern in planning for water development. So have the collection and interpretation of adequate basic data, the coordination of multiple-purpose planning, the establishment of integrated basin planning, planning for related land-use practices, and the relation to use of other resources. The systematic promotion of technical innovation and its timely application also have been problems of planning. Problems connected with the realization of development most frequently have concerned financing—whether private or public funds should be used, the degree of repayment to be required, and the financing of research and experiment. Problems related to operational management have been seen in water quality control, the jurisdiction of different levels of administration, priorities in water use, and the relation of planning, construction, and management agencies. The relation of water resources to the operation or use of other facilities or resources also has been a notable problem. The latter has been illustrated in the opposition of the coal industry to hydroelectric-power development in some parts of the country, and in the perennial problem of the competition of inland navigation facilities with rail carriers.

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[44] Ackerman and Löf, op. cit., p. 351.

Some of these problems have survived and remain appropriate for consideration in a policy review like that of the select committee. A number of them have been resolved at least adequately in the past. However, the needs of the future bring forth still others. Their identification is an essential prolog to decisions on policy change.

V. Some General Problems of Future Development

An activity as pervasive as water development may be expected to have deep roots in the physical, economic, and institutional characteristics of the Nation. Both our strengths and our problems are profoundly related to these characteristics. Among them are—

The United States is a country of large river basins. Six major basins include nearly three-fourths of the land area of continental United States.

Two great regions, one eastern and one western, have distinctly different characteristics of water supply. In the past they also have had distinctly different types of water demand, the requirements of the West being heavily dominated by the use of water for irrigation.

Private ownership of the means of economic production and distribution is dominant in the Nation. Accordingly, the economy of the country is dominated by judgments of the marketplace in the satisfaction of consumer demand. This process has been modified substantially for the provision of water and water-derived services, which depends in part upon socially based political and governmental decision.

Constitutional law affords the basic legal framework for the organization of water development. The interstate commerce clause and other constitutional provisions furnish a distinctive legal structure requiring regulation as well as encouraging Federal participation in water development.

The 50 State jurisdictions within the United States have little correspondence with the limits of the major drainage basins, or even with the limits of the important tributary basins. In addition, hundreds of county, municipal, and special district jurisdictions over water are found within the State borders. Fragmentation of user interest and developmental responsibility is typical of our water administration. For example, within the Delaware River watershed, a relatively small basin, there are more than 100 Federal, State, and municipal governmental entities concerned with the planning and eventual operational management of water facilities. A large number of private corporations are interested in the use of the same water, and a few also have operational interests.

These features of the institutional and physical environment of the Nation form a background against which a few general problems of future development may be readily understood. They are: Recognition of new types of regional requirements, program design for different scales of development, the weighting of future obsolescence in program design and financing, and the coordination of Federal operations with those of other public or private agencies having impinging areas of interest.

RECOGNITION OF NEW TYPES OF REGIONAL REQUIREMENTS

One great regional or sectional difference within the United States has been of classic significance for water policy. This is the difference between the 17 Western States which contain arid or semiarid lands and the 31 Eastern States and their humid environment. The classic interest of the East has centered on flood control and navigation, whereas that of the Western States has been concerned with irrigation and more recently with irrigation, electric power, and flood control. Important as it has been for the past, there can be little question that the simple distinction between East and West no longer will suffice as the basis for policy formation.

The phenomena of urbanization and industrial growth already have affected both East and West profoundly. Their further influence in the future is almost certain to make them basic factors for future water-development policy. The test of any policy or procedure, and indeed its origin, is likely to be in extreme conditions. Thus the origin of our reclamation policy and the tests of its success lay in the perennial drought conditions of the western Great Plains and intermontane basins. The tests of our flood-control policy have come in its success in meeting the conditions encountered in the Ohio Basin and on the lower Mississippi.

The extremes of the future likely to be encountered as tests of the success of Federal policy are likely to be found in both East and West, but in the areas where urban and industrial growth are indicated as most likely. These are certain to come within the group of nine Southwestern States previously described in this report, and within the States of the northeastern-midwestern urban zone.

The Southwestern States generally include those basins described by the select committee as Central Pacific, South Pacific, Great Basin, Colorado, Upper Rio Grande, and Pecos, Upper Arkansas-Red, and Western Gulf.

The rising population of these areas, indications of their rising per capita water requirements, and their limited runoff promise to bring total water requirements uncomfortably close to the limits of natural supply by the year 2000 (see app. 11). Something more than the traditional approach to water development will be required to meet the problems of the Southwest. It is likely that not even integrated multiple-purpose development will suffice to bring water demand and water supply into balance if the expected and desired economic and population growth are to be supported.

The second great region to be considered in future water policy is the northeastern-midwestern urban region. This region covers all or an important part of 19 States in the northeastern quadrant of the country, lying generally within the basins described by the select committee as Lower Missouri River, Upper Mississippi River, Ohio River, Western Great Lakes, Eastern Great Lakes, Delaware and Hudson Rivers, New England, and Chesapeake Bay (including the Potomac River). This is the region, as will be remembered, within which most of the population and industrial growth of the country are expected during the remainder of this century. The density of this coming occupance and the humid physical environment combine to create a somewhat different set of problems for water development in this region as compared with the Southwest. The great numbers of people involved, and the industrial growth needed to support them, will create conditions that also will be tests for future development policy, but of a different sort from those of the Southwest. The problems which can be anticipated in this region generally concern quality control of water and treatment therefor, the adequacy of inland navigation facilities, the adequacy of water recreation facilities available to the public, and the adequacy of flood prevention measures. Again these requirements promise to reach beyond the capacities of the traditional development procedure of the immediate past.

The description of these two regions as areas within which the heaviest pressure upon the water resource is likely to be reached, and therefore the most stringent tests of policy, does not mean the absence of development problems elsewhere in the country. Indeed, heavier requirements for future development exist within the remaining two regions, the Southeast and the eight Northwestern States, but inadequacies of procedure are less likely to be felt within them because of the generally higher ratio of resources to population anticipated within this century. These two regions have some striking general similarities in the problems which they present for development in the future, in spite of the obvious physical differences and their contrast in the past. Both are regions upon which the country will depend heavily for further expansion of agricultural production through irrigation. About two-thirds of the net additions to irrigated acreage estimated by the U.S. Department of Agriculture as required for projected high population levels by the year 2000 fall within these two regions.[45] In addition, these are regions in which some industrial and urban growth may be expected, but generally of a more dispersed nature than in the other regions. In general, these two regions may be characterized as having less pressure upon their water resources than the other two, considerable potentiality for agricultural development, and as areas of dispersed industrial growth.

Recognition of these sectional differences can provide a useful generalization for judging the adequacy of present or proposed water policies. Judged by the standards of the remainder of the world each of the regions described has distinctive characteristics, and each is equivalent to a nation in area and population. They would seem the largest sectional units that could be used for forming and testing future Federal water policy.

SCALE OF DEVELOPMENT AND PROGRAM DESIGN

The basic reason why both multiple-purpose development and integrated basin development of water resources have achieved a permanent place in planning and construction lies in the economies of scale which they afford. Other things being equal, the larger the capacity of a reservoir, the lower the capital costs per acre-foot of storage.[46] Or the larger the head which can be taken advantage of through strategic construction of hydro generating plants along the entire course of a stream, the greater the benefits from a given acre-foot of water stored. In a like manner, even interbasin diversions present some possibilities of scale economies.

Full use of scale economies in integrated development

One of the problems of the future is that of the extent to which the economies of scale and other economies from integration already indicated as possible will actually be achieved through multiple-purpose integrated basin development. There are some major streams, like the Columbia River, where present system design is not yet taking full advantage of these possible economies.[47] Wherever there are divided jurisdictions, either because of an international border or because of State compact division of water, such problems exist or may be expected.

One of the interesting and as yet little studied questions in hydraulic planning is an examination of the entire Mississippi system as a unit. Although plans have been drafted and to a degree implemented for the major tributaries of the Mississippi, the characteristics of the entire system as an integrated unit have been given little attention. The now famous House Document No. 308 (69th Cong., 1st sess.) separates the Arkansas, Ohio, and Missouri basins from the Mississippi for separate consideration in the hydraulic studies which it directed. The importance of both the upper and lower Mississippi in future irrigation plans, the potentialities of a better integrated inland navigation system as related to the great northeastern-midwestern urban zone, and the gigantic size of this system now make it a tempting subject for exploring total system design. It is possible that the time already may be past when the major benefits from such planning and development could be realized. However, its possibilities at least make it deserving of study (fig. 8).

Coordination of tributary and main-stem development

There are two remaining aspects of the problem of achieving scale economies through water development which are worthy of consideration in policy review. They are the coordination of tributary development and main-stem river basin development, implied in the above discussion of the Mississippi Basin, and the achievement of scale economies in the water-related services.

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[45] U.S. Department of Agriculture, "Land and Water Potentials and Future Requirements," a report to the Senate Select Committee on National Water Resources, Washington, D.C. (1959), tables 43 and 46.

[46] The actual function representing economies of scale in reservoir construction will differ as site conditions, location, engineering design, and other conditions differ. Robert Dorfman, Harvard Program of Research in Water Resources Development, has given a typical simple hypothetical form which he applied to a benefit maximization problem in a hypothetical basin. In symbols it is:

$$C(X)=\frac{43X}{1+.2X};$$

where C is the capital cost of construction and X is any given capacity in acre-feet. (Robert Dorfman, "Design of the Simple Valley Project," paper presented at the Symposium on the Economics of Watershed Planning, Tennessee Valley Authority, Knoxville, Tenn., June 10-12, 1959 (July 1959 revision). See also figs. (A) and (C), app. 4 of this report for graphic descriptions of this function.

[47] Illustrated in the sequence and timing problem described by John V. Krutilla in "Sequence and Timing in River Basin Development," Resources for the Future, Inc., 1960.

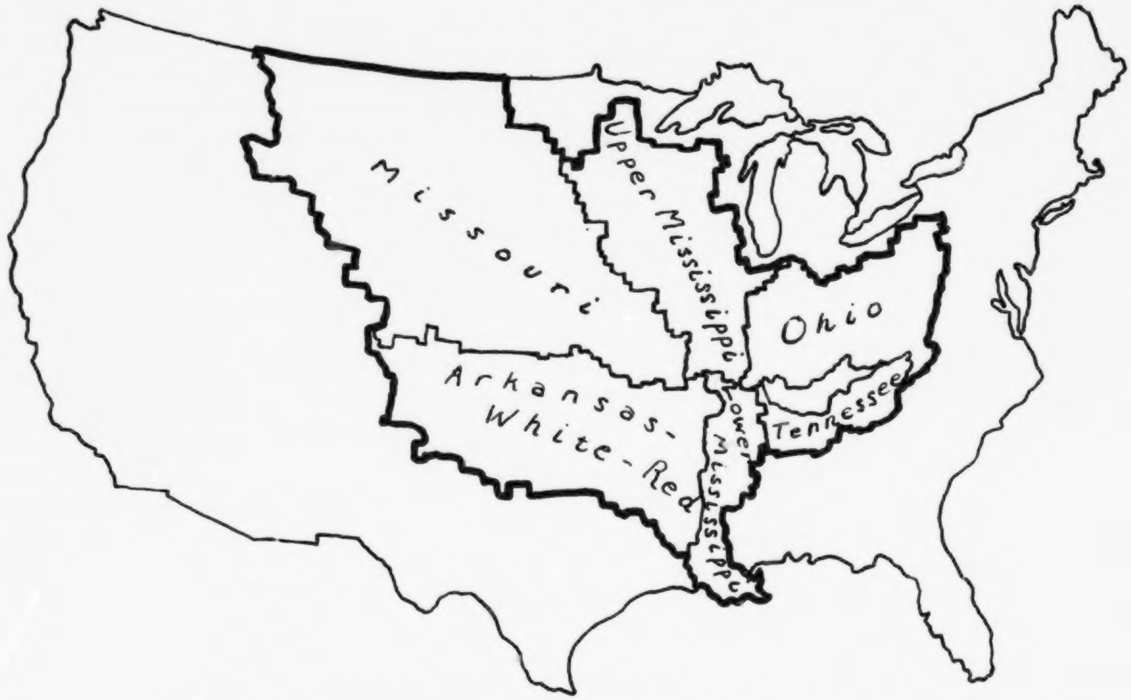

FIGURE 8.—The Mississippi River Basin, including its principal tributary basins.

The coordination of tributary development and main-stem development perhaps has had its most vivid illustration in the upstream-downstream storage controversy which has been nourished in some quarters for at least a decade. Unfortunately, this controversy, as popularly presented, often has taken on an either/or complexion. In fact, however, it is not a question of upstream works versus big dams, but of the coordinated planning of the two. Each has its appropriate and valuable place. The existence of the controversy does point to the fact that our planning in this instance has been incomplete in the past. The great advantages of scale conferred by the techniques which have made large reservoirs possible have brought a concentration of attention upon the main stems of our streams without full planning for some of the tributaries. An example occurred in the development of the Kansas River Basin, where crisis-generated plans for Kansas City flood control omitted consideration of upstream agricultural and municipal needs.[48] The development there encouraged in the interest of scale economies and as part of a basinwide plan seems to have leaped over the more localized needs of the smaller tributary basins. The subject still is a fertile source of public discussion among those interested in the development of the Kansas basin.[49] The temptation and even the drive to take advantage of the scale economies in our future water development thus must be tempered with the realization that different scales of requirements must be considered in planning the full development of a large river basin. This is one reason that a complete design for the entire Mississippi system which takes full advantage of the scale economies would be an enormously complex task. However, even for smaller basins the question of adequate planning for different levels of requirement still remains. This is a question for which the experimental application of operations analysis methods may provide helpful direction of physical design.

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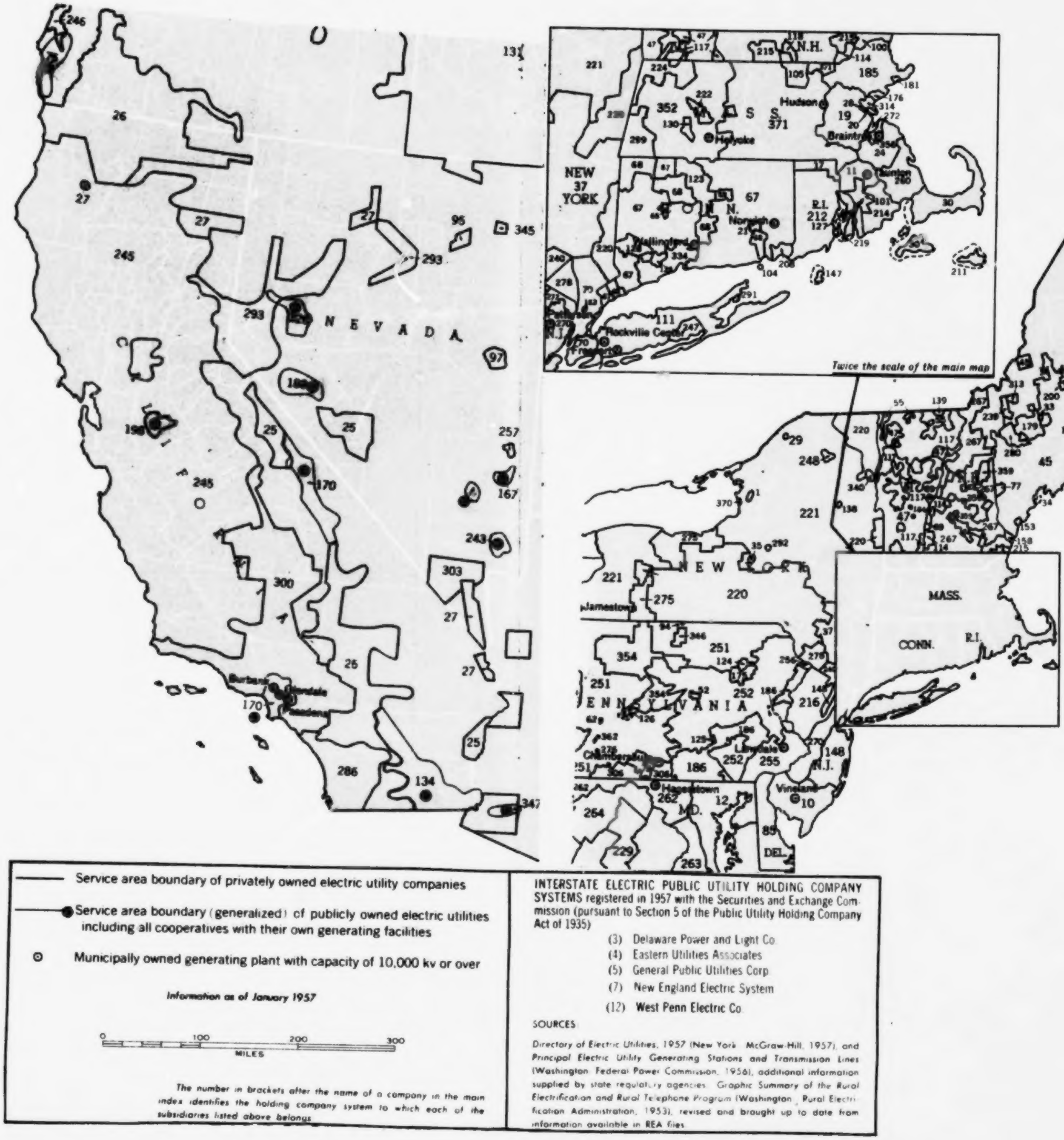
[48] See University of Kansas, "The Kansas Basin, Pilot Study of a Water shed," Lawrence, Kans., 1956, p. 103.

[49] See transcript of hearings of the Senate Select Committee on National Water Resources at Topeka, Kans., Nov. 18, 1959.


NEVADA
NEW YORK
MASS.
N.H.
CONN.
R.I.
PENNSYLVANIA
N.J.
MD.
DEL.
Hudson
Holyoke
Braintree
Taunton
Wallingford
Norwich
Rockville Centre
Freeport
Jamestown
Chambersburg
Hagerstown
Lansdale
Vineland
Burbank
Glendale
Pasadena
Twice the scale of the main map
MILES
0
100
200
300

Service area boundary of privately owned electric utility companies

Service area boundary (generalized) of publicly owned electric utilities including all cooperatives with their own generating facilities

⊙ Municipally owned generating plant with capacity of 10,000 kv or over

Information as of January 1957

The number in brackets after the name of a company in the main index identifies the holding company system to which each of the subsidiaries listed above belongs

INTERSTATE ELECTRIC PUBLIC UTILITY HOLDING COMPANY SYSTEMS registered in 1957 with the Securities and Exchange Commission (pursuant to Section 5 of the Public Utility Holding Company Act of 1935)

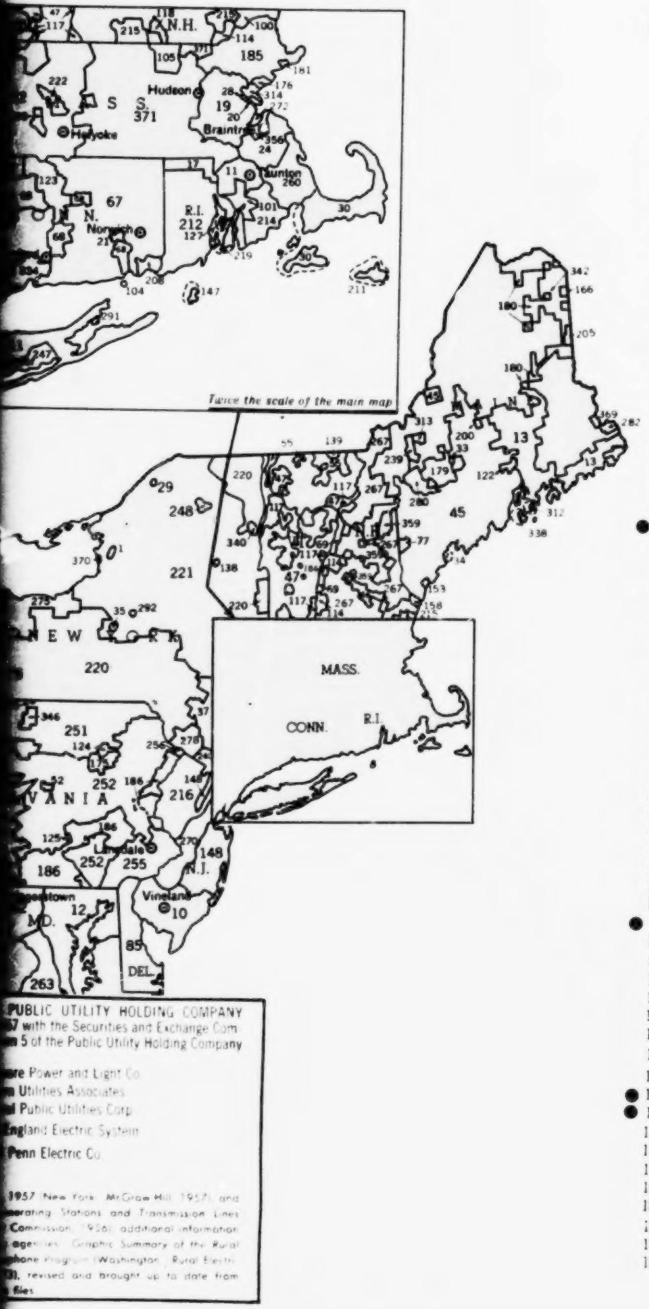
(3) Delaware Power and Light Co
(4) Eastern Utilities Associates
(5) General Public Utilities Corp
(7) New England Electric System
(12) West Penn Electric Co

SOURCES

Directory of Electric Utilities, 1957 (New York McGraw-Hill, 1957), and *Principal Electric Utility Generating Stations and Transmission Lines* (Washington Federal Power Commission, 1956), additional information supplied by state regulatory agencies. *Graphic Summary of the Rural Electrification and Rural Telephone Program* (Washington, Rural Electrification Administration, 1953), revised and brought up to date from information available in REA files

FIGURE 9. New England, Mid-Atlantic States, and California Electric Powe Service Areas. (From Ackerman and Löf, *Technology in American Water Development*, United States Electric Power Utility Service Areas, pocket map Johns Hopkins Press, 1959.)

37a


N.H.
MASS.
Hudson
Braintree
Holyoke
Taunton
N.
Norwich
R.I.
Twice the scale of the main map
NEW YORK
MASS.
CONN.
R.I.
VANIA
Lansdale
Vineland
N.J.
MD.
DEL.
PUBLIC UTILITY HOLDING COMPANY
7 with the Securities and Exchange Com
n 5 of the Public Utility Holding Company
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d Public Utilities Corp
England Electric System
Penn Electric Co
1957 (New York: McGraw-Hill, 1957), and
erating Stations and Transmission Lines
Commission, 1956); additional information
agencies; Graphic Summary of the Rural
phone Program (Washington: Rural Electri
0), revised and brought up to date from
files

	1	Adams Electric Light Co
●	4	Alamo Power District No 3
	10	Atlantic City Electric Co
	11	Attleboro Steam & Electric Co (7)
	12	Baltimore Gas & Electric Co
	13	Bangor Hydro-Electric Co
	17	Blackstone Valley Gas & Electric Co (4)
	18	Border Counties Power Coop Inc
	19	Boston Edison Co
	20	Boston Gas Co
	24	Brockton Edison Co (4)
	25	California Electric Power Co
	26	California Oregon Power Co
	27	California-Pacific Utilities Co
	28	Cambridge Electric Light Co
	29	Canton Electric Light and Power Co
	30	Cape and Vineyard Electric Co
	33	Carrabasset Light & Power Co
	34	Casco Bay Light & Power Co
	45	Central Maine Power Co
	47	Central Vermont Public Service Corp
	55	Citizens Utilities Co (Vt)
	62	Colver Electric Co
	66	Concord Electric Co
	67	Connecticut Light & Power Co
	68	Connecticut Power Co
	69	Connecticut Valley Electric Co
	70	Consolidated Edison Co of New York Inc
●	75	Coos-Curry Electric Coop Inc
	77	Cornish and Kezar Falls Power & Light Co
	85	Delaware Power & Light Co
	91	Eastern Shore Public Service Co of Md (3)
	95	Elko Lamoille Power Co
	100	Exeter & Hampton Electric Co
	101	Fall River Electric Light Co (4)
	104	Fisher's Island Electric Corp
	105	Fitchburg Gas & Electric Light Co
	111	Long Island Lighting Co
	114	Granite State Electric Co (7)
	117	Green Mountain Power Corp
	118	Greenville Electric Lighting Co
	122	Hampden & Newburg Light & Power Co
	123	Hartford Electric Light Co
	124	Harvey's Lake Light Co
	126	Home Elec Co
	127	Homestead Utilities, Inc
	128	Housatonic Public Service Co
	130	Huntington Electric Light Co
	131	Idaho Power Co
●	134	Imperial Irrigation District
	138	Indian Lake Power & Light Co
	139	International Electric Co
	147	Island Light and Power Co
	148	Jersey Central Power & Light Co (5)
	153	Kennebunk Light & Power Co
	158	Kittery Electric Light Co
	163	Lawrence Park Heat, Light & Power Co
	166	Limestone Electric Co
●	167	Lincoln County Power District No 1
●	170	Los Angeles Dept of Water & Power
	175	Luzerne County Gas & Electric Co
	176	Lynn Gas & Electric Co (7)
	179	Maine Consolidated Power Co
	180	Maine Public Service Co
	181	Manchester Electric Co
	184	Meriden Electric Light & Power Co
	185	Merrimack-Essex Electric Co (7)
	186	Metropolitan Edison Co (5)
●	188	Mineral County Power System
●	198	Modesto & Turlock Irrigation Districts
	200	Monson Light & Power Co
	204	Monterey Utilities Corp (12)
	205	Monticello Electric Co
	208	Mystic Power Co (7)
	211	Nantucket Gas & Electric Co
	212	Narragansett Electric Co (7)
	214	New Bedford Gas & Edison Light Co
	215	New Hampshire Electric Co
	216	New Jersey Power & Light Co (5)
	219	Newport Electric Corp
	220	New York State Electric & Gas Corp
	221	Niagara Mohawk Power Corp
	224	Northern Berkshire Electric Co (7)
	229	Northern Virginia Power Co (12)
	239	Oquossoc Light & Power Co
	240	Orange & Rockland Electric Co
●	243	Overton Power District No 5
	245	Pacific Gas & Electric Co
	246	Pacific Power & Light Co
	247	Patchogue Electric Light Co
	248	Paul Smith's Electric Light, Power & RR Co
	251	Pennsylvania Electric Co (5)
	252	Pennsylvania Power & Light Co
	255	Philadelphia Electric Co
	256	Pike County Light & Power Co
	257	Pioche Power & Light Co
	260	Plymouth County Electric Co
	262	Potomac Edison Co (12)
	263	Potomac Electric Power Co
	264	Potomac Light & Power Co (12)
	267	Public Service Company of New Hampshire
	270	Public Service Electric & Gas Co
	272	Quincy Electric Co (7)
	275	Rochester Gas & Elec Corp
	276	Rockingham Light, Heat & Power Co
	277	Rockland Electric Co
	278	Rockland Light & Power Co
	280	Rumford Light Co
	282	St Croix Electric Co
	286	San Diego Gas & Electric Co
	291	Shelter Island Light & Power Co
	292	Sherrill-Kenwood Power & Light Co
	293	Sierra Pacific Power Co
	299	Southern Berkshire Power & Electric Co (7)
	300	Southern California Edison Co
	303	Southern Nevada Power Co
	306	South Penn Power Co (12)
	312	Stonington & Deer Isle Power Co
	313	Stratton Light Co
	314	Suburban Electric Co (7)
●	328	Truckee-Carson Irrigation District
	334	United Illuminating Co
	338	Vinalhaven Light & Power Co
	340	Wadhams & Westport Power & Light Corp
	342	Washburn Electric Co
	345	Wells Power Co
	346	Wellsboro Electric Co
●	347	Wellton-Mohawk Irrigation & Drainage D
	352	Western Massachusetts Electric Co
	354	West Penn Power Co (12)
	356	Weymouth Light & Power Co (7)
	359	White Mountain Power Co
	362	Windber Electric Corp
	369	Woodland Light & Water Co
	370	Woodville Electric Light & Power Co
	371	Worcester County Electric Co (7)

England, Mid-Atlantic States, and California Electric Power (From Ackerman and Löf, *Technology in American Water De-* States Electric Power Utility Service Areas, pocket map, ress, 1959.)

Achievement of scale economies in water-related services

By far the most important water-related service[50] is in the generation and distribution of electricity. The very rapid growth of generation and electricity use during the last 30 years has provided many interesting examples of the economies of scale; it has also provided some outstanding examples of the way in which organization about hydroelectric power generation can form potent stimuli toward economies of scale and the sale of electricity at very low cost.

Future generation and distribution of electricity is very likely to be characterized by these conditions:

(*a*) A very rapid rate of increase in electricity requirements and in total generation from all sources. Electricity requirements by the year 2000 may be as much as seven times those of 1959, indicating a possible rate of growth much outstripping that of population.

(*b*) Most of the vast additions to generating capacity will be fuel-powered plants rather than hydroplants.[51] They will be either fossil fuels or, during the latter years of the century, nuclear fuels.

(*c*) Measures which can achieve cost reductions and rate reductions for the electricity produced and consumed in the future will continue to be economically and socially desirable.

The high proportion of fuel-powered plants which will characterize future electricity generation does not mean a role of insignificance for existing and future hydro-generating units. Their importance in providing capacity at periods of peak loads may even enhance the value of hydro. This is mentioned because past development has shown that hydro generation can be the basis for organizing systems of large enough extent to support large-scale, low-cost fuel-powered plants. This applies to both privately operated and publicly managed generation. In this connection two facts are of future policy interest: Many of the utility service areas in the northeastern and midwestern sections of the country are not of sizes which encourage the establishment of large-scale plants. This is illustrated by data on generating plant capacities in New England, which has many small service areas, and in California, which has relatively large power service areas. (Table 7 and fig. 9.) Both reflect practices in privately operated systems. Most New England plants are of a small size that Californians have hardly bothered with. Only 23 percent of the total number of New England public utility generating stations in 1959 had installed capacities of 100,000 kilowatts or more. The economies of scale achieved within the larger generating units and larger plants are substantial. Typical operation and maintenance costs for a 65-megawatt unit may be three times those of a 500-megawatt unit. Total costs per kilowatt-hour of a 15-megawatt unit may be nearly twice those of a 200-megawatt unit (see app. 9). Sixty percent of all U.S. utility operating companies were reported in 1957 as having peak loads of less than 125,000 kilowatts. Those with peak loads in excess of 500,000 kilowatts were only 14 percent.[52] In view of the fact that size of service area may have some relation to past Federal legislation,[53] utility system size appropriately might be considered in a review of the relation of water development to electricity production. Although a number of electric utility companies were under holding company control prior to 1935, most of the holding companies divested themselves of subsidiaries in such a way that the latter now are exempt from Federal regulation, being entirely under State jurisdiction. Because State boundaries do not necessarily coincide with logical electric service areas, the optimum size of geographical area was attained only by coincidence.[54] In recent years some power "pools" have been organized cooperatively by adjacent systems. These pools can and do take advantage of large-scale generation, and may be one effective method of achieving scale economies. The Northwest Power Pool, covering the Pacific Northwest, is notable among them. However, "interconnected" systems, the typical relation between neighboring U.S. electric utilities, are not designed to take advantage of these economies.[55]

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[50] A "water-related service" is one which can be provided by water, but also by other means. Recreation and transportation are other examples.

[51] An increase of about 1,333,000,000,000 kilowatt-hours in electricity consumption between 1955 and 1975 has been projected by Resources for the Future, Inc. Of this only about 145,000,000,000 kilowatt-hours, or 10.8 percent, is estimated as being served by hydrogeneration. (Sam H. Schurr, "Past and Prospective Demands" in "Two Statements on the Nation's Energy Position," Resources for the Future, Inc., 1959, p. 20.)

[52] "National Association of Electric Companies Legislative Abstract," vol. II, No. 16, Oct. 28, 1957, p. 1.

[53] The specific legislation referred to is the Public Utility Holding Company Act of 1935 (act of Aug. 26, 1935, 49 Stat. 303).

[54] See also Ackerman and Löf, op. cit., p. 505.

Table 7.—*Thermal electric stations in New England and California by size groups*

	Number of stations	
	New England	California
Installed generating capacity (in thousand kilowatts):		
Less than 1	2	0
1 to 4	5	1
5 to 9	6	0
10 to 19	14	1
20 to 49	22	2
50 to 99	7	9
100 to 199	8	6
200 to 299	6	2
300 to 399	1	8
400 to 499	2	1
500 to 599	0	4
600 to 700	0	1
Total	73	35
Percent 100 to 700,000 kilowatts	23	63

Source: Federal Power Commission files. Data include plants operated by electric utilities only.

THE WEIGHTING OF FUTURE OBSOLESCENCE IN PROGRAM DESIGN AND FINANCING

Any program of the scale necessary for at least 150 million additional people and needed for the higher level of living of the entire 330 to 380 million population projected for the year 2000 raises a serious question of obsolescence. This has not been a question of any past prominence because the Nation's development program has attained substantial size only within the last two decades. Furthermore, legacies of obsolescent facilities thus far have been small. However, if efficiency is sought for future development, the possibility of obsolescence must be considered in policy formation. There are three reasons for such consideration: (*a*) The vast size of the capital investment required in the remainder of this century can make the assumption of long service lives for facilities costly errors of judgment, in their total sum; (*b*) the rapidly increasing rate of technological progress which is indicated (see sec. II) greatly increases the risks of obsolescence by comparison to anything which the Nation has experienced hitherto; (*c*) in spite of these facts, in some quarters there has been an increasing tendency to press for the assumption of increasing length of life in benefit-cost evaluations of water facilities, or in drafting of amortization schedules for them.

This question deserves deeper and more detailed exploration than can be given in this report. However, the nature of the questions involved may be generally indicated in a few comments.

Facilities used for a stream regulation, and for the production of water or water-derived services like hydroelectric power, obviously have different service lives, and different risks of obsolescence within a given period. Land used for a site and any vegetative cover protecting or enhancing site attributes may be assumed to have an indefinite service life. Dams or other detention works for storage may be assumed to have a relatively long physical life where they receive only nonturbid water. In actual practice, however, sediment deposition does limit the assumed useful life of most reservoirs. A period of at least 100 years is not uncommon among major dam and reservoir works and some may have considerably longer lives. Risk of obsolescence within the periods here set for policy review, 1960–2000, therefore is very low for detention works. It is clear that technology still is capable of affecting construction costs of major works. Construction very far in advance of requirements therefore may not be prudent policy. At the same time, assumptions as to the service life of facilities that are constructed can be considered reasonably stable.

Although they form a less important part of total costs on an incremental basis, the remaining facilities associated with water development, like turbines, generators, control gates, etc., have much higher risks of obsolescence. It is reasonable to expect that the accelerating rate of scientific and technological effort will bring higher and higher probabilities of influential changes in costs of producing energy, manner of agricultural production, costs of transportation, and other facilities related to the final use of the water. The assumption of a service life of any great length for many facilities directly connected with the final use of water therefore seems unrealistic.

This problem may be summarized in this way. For the major regulation works risks of technological obsolescence are relatively slight and service lives can be accurately determined. On the other hand, the risk of obsolescence from the effects of technical improvement is high for many works immediately associated with production, like irrigation distribution works, and electric energy generation facilities. This fact is of significance in the calculation of rates of return from vendible services and the confidence which can be placed in exact schedules of repayment. Many of them probably should be rated as having a high risk of obsolescence beyond a period somewhere between 25 and 40 years, depending on the type of facility.

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[55] See Electrical World, "Interconnected Systems Link 85 Percent of U.S. Capacity," vol. 152, No. 19, Nov. 9, 1959, pp. 54–55, for an account of present interconnections and pools.

The risks of technological obsolescence also suggest the desirability of incorporating a high degree of flexibility into physical design. It is entirely possible that system flexibility or adaptability to all reasonable uses, should be a positive criterion for design. That is, an adaptable system with fewer immediately foreseeable net benefits would be preferable to a rigid system with more immediately foreseeable net benefits. Under such a policy multiple-purpose units, particularly dams and storage reservoirs, would be designed for adaptability to all reasonably expectable uses. Furthermore, large capital investments for single purposes would be built only as needed, and amortized on the basis of realistic service life expectancy.

COORDINATION OF FEDERAL OPERATIONS WITH THOSE OF OTHER PUBLIC OR PRIVATE AGENCIES HAVING IMPINGING AREAS OF INTEREST

Any situation like that of the United States at present and in the immediate past foreordains problems of administrative coordination. The large river basins divided among several or more State jurisdictions in a Federal system, the division of entrepreneurship between public and private agencies and among public agencies of different types, and the growing opportunities for exploitation of scale economies have created complex problems of coordination which have not yet been solved fully. With increasing needs for efficiency in the future, the attractiveness of the scale economies and more complex methods of development are likely to aggravate coordination problems as among Federal, State, municipal, and private agencies. The existence of more than a hundred interested agencies within a single river basin of modest size, as noted above for the Delaware,[56] gives some indication of the possible extent of these problems.

There are two types of these problems. One might be described as vertical coordination (or integration), and it concerns the relations of the organizations responsible for activities at different levels between planning and final distribution of services. The necessary coordination between a Federal agency building and operating a storage project and an irrigation district is an example. Another example of this type is the coordination required between an electricity generating agency, or company, and electricity distribution cooperatives, municipalities, or companies. In general, it may be said that problems of this type have been met satisfactorily from a technical point of view, even though they may not have been satisfactorily treated from the point of view of all special interest objectives.[57]

The second type of problem may be described as one of horizontal coordination (or integration). This is the problem presented in divided geographical jurisdiction of agencies, Federal and non-Federal. It is the most knotty problem of the future, if the economies of scale are to be fully taken advantage of. It is the one in which there are many unsolved local and regional difficulties which are likely to be intensified in the future as the pressure for efficient development increases. Typical problems of the past were represented in the opportunities which existed for integrated multiple-purpose development and water control in the Tennessee, Missouri, and Columbia River Basins. Properly unified or coordinated operation offered very substantial economies of scale in all three instances. On the Tennessee the problem was met by assigning most development and water management functions to a single regional agency, the Tennessee Valley Authority; on the two other rivers an answer was found in close coordination among the agencies operating on a national basis, the Corps of Engineers, the Department of the Interior, and the Department of Agriculture, with the cooperation of some State, local, public, and private agencies. In all cases economies of scale were certainly achieved. For one important development of the future, the California State water plan, a single State has been in the position of providing leadership for taking advantage of economies of scale while at the same time answering a political problem of mounting regional requirements.

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[56] Walter Phillips, "Administrative Aspects of Delaware River Basin Water Resource Planning and Development," address before the American Society for Public Administration, Jan. 29, 1957.

[57] Full satisfaction of all special interest objectives is in most cases a practical impossibility.

The successes of the past as well as the clearly indicated problems of the future suggest this as a most important point for policy review. Three aspects of this type of problem may be of special interest in the future. One is assurance that the economies of scale realizable through coordinated or integrated multiple-purpose development will in fact be realized in future water control operations on all streams where they are of significance. A second problem is assurance that the benefits from economies of scale may be available within all parts of the country where they are reasonably attainable. For example, should public encouragement be provided which will stimulate private electric utilities to take advantage of economies of scale which might benefit the residents and industries in their service areas? Moves toward efficiency based upon a hydraulic system lose a good part of their effectiveness if the benefits cannot be passed on to the ultimate consumers, whatever the reason.

A third aspect worthy of policy consideration is assurance that locally initiated development serves the cause of efficiency over the long run. For example, extensive development of groundwater deposits on the high plains, particularly in Texas, has been very profitable on the basis of mining the aquifers. This has been done entirely under the entrepreneurship of private farm operators and local districts. Continuation of the present practices of exploitation may be entirely justified. On the other hand, the end of economically mined water at some future date may create problems of rehabilitation or supplementary development which heavily involve future Federal participation. Hence, study is needed to determine whether or not the present pattern of development is the most efficient over the long run, considering both private investment and probable needed public investment in such water facilities.

VI. Future Comprehensive Development and Related Special Problems

The general problems which have been outlined above clearly indicate that a situation will be reached at some time within this century where water requirements will cause the nation to go beyond traditional approaches to water development, including those of integrated multiple-purpose development as now practiced. The evolution of a new type of development already is foreshadowed by present interest in means of making water available which are not commonly included in the planning procedures of the existing development agencies. These already have been reviewed in section III of this report. For a new type of approach which will include these techniques as a routine part of planning, the term "comprehensive development" here is suggested.

The term comprehensive development frequently has been applied to our planning, construction, and operational management of water facilities in the past. As we now understand the techniques of water development, we have not yet achieved such a state of organization at any time. By comprehensive development we mean not only the application of integrated multiple-purpose design, but also planning and management which include the joint consideration of ground and surface waters, conservational and other measures for "engineering" of demand, and the treatment and management of waters having substandard quality. Consideration of every appropriate technique would be a routine part of planning for such development. It is the thesis of the remainder of this report that comprehensive development will be achieved by the United States as standard practice at some time during the remainder of this century. It is believed that its application, understood in these terms, will be mandatory at least in the southwestern nine States, and probably also in the northeastern-midwestern urban zone. The relative value or probable need for considering the different techniques which were included within this definition of comprehensive development is set forth in table 8, by river basin. The probable appropriateness of applying most techniques to all of the southwestern basins can be clearly seen. If the techniques centered primarily on rural land use (forest and range management and water conserving agronomy) are disregarded, the somewhat less urgent but still indicative situation of the mid-

TABLE 8.—*Applicability of some techniques of comprehensive development, by river basin, 1960–2000*

POTENTIAL VALUE OF APPLYING SOME TECHNIQUES OF COMPREHENSIVE DEVELOPMENT, BY RIVER BASIN, 1960-2000

Basin or Basins	Basin system design of multipurpose works	Interbasin systems	Added groundwater, including integration with surface	Recycling	Planned location of demand	Weather modification	Forest and range management for water yield	Water-conserving agronomy	Desalting	Sediment control	Organic waste treatment	Chemical waste treatment	Use priority by water quality
A. Southwestern States													
1. Central Pacific and South Pacific	■	■	■	■	■	■	■	■	■	■	■	■	■
2. Great Basin	▨	■	■	■	■	■	■	■	■	■	▨	▨	■
3. Colorado	■	■	■	■	■	■	■	■	■	■	▨	▨	■
4. Upper Rio Grande and Pecos	▨	■	■	■	■	■	■	■	■	■	▨	▨	■
5. Upper Arkansas—Red	■	■	■	■	■	▨	■	■	■	■	▨	■	■
6. Western Gulf	▨	■	■	■	■		■	■	■	■	■	■	■
B. Northwestern States													
1. Pacific Northwest	■	▨	▨			▨	▨			▨	▨	▨	
2. Upper Missouri	■	■	■	▨	▨	▨	▨	▨	■	■	▨	▨	■
C. Southeastern States													
1. Tennessee and Cumberland[a]	▨	▨			▨	▨				■	■	■	
2. Southeast Rivers	▨	▨	■		■	▨				■	■	■	
3. Lower Mississippi, Arkansas, Red, White	■	■	■		■					■	■	■	▨
D. Midwestern-Northeastern Urban Zone													
1. Upper Mississippi and Lower Missouri	■	▨		▨	■					■	■	■	
2. Eastern and Western Great Lakes	▨	▨									■	■	
3. Ohio	■			▨	■	▨				■	■	■	▨
4. Chesapeake Bay	■		▨	■	▨	▨			▨	■	■	■	▨
5. Delaware and Hudson	▨	▨	▨	■	■	▨			▨	▨	■	■	▨
6. New England	▨	▨			■	▨					■	■	

OPPORTUNITY FOR DERIVING BENEFIT WITHIN A GIVEN BASIN b/

■	Good
▨	Some
□	Slight

[a] Tennessee and Cumberland Basins already have a high degree of integrated multipurpose development.

b/ Scale of Values intended for intra - columnar comparison only.

western-northeastern urban zone also can be seen. The values also appear for both the Southeastern and Northwestern States, although the numbers of people affected in both instances are considerably less than those for the other two regions. By applicability we mean the opportunities for reaping further benefits within a given basin, assuming in some cases perfection of a technique now under experiment or pilot plant investigation. (Basins mentioned on table shown in fig. 10.)

THE RELATED PROBLEMS

If comprehensive water development (as here defined) is accepted as a necessary part of future national procedure, present practice and policy have some inadequacies. A few of these inadequacies have been noted as past problems, and their outlines well defined in water policy commentary; their importance, however, becomes greatly enhanced if the need for comprehensive development is accepted, and the large scale of future water requirements is realized.

Six further problems are therefore presented for policy consideration, in case comprehensive development is considered by the committee to be desirable future practice. They are: (*a*) the preservation of reservoir and dam sites; (*b*) fundamental research in related scientific disciplines; (*c*) collection and interpretation of basic data; (*d*) experiment with innovations in development procedures; (*e*) means of evaluating progress and reviewing experience; and (*f*) the choice of Federal functions.

Preservation of reservoir and dam sites

Although technology has increased the range of sites which are physically and engineeringly feasible for economical water storage, such sites still are limited in number. Many of them already are identified. If the premise of this report is accepted—the need to plan now for ultimate full regulation [58] of all major streams—then protection or reservation of remaining sites seems prudent. If efficiency is sought in future development, sites need protection against any new encumbrance by other uses, and against new

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[58] See sec. VII 2 for a definition of "full regulation."

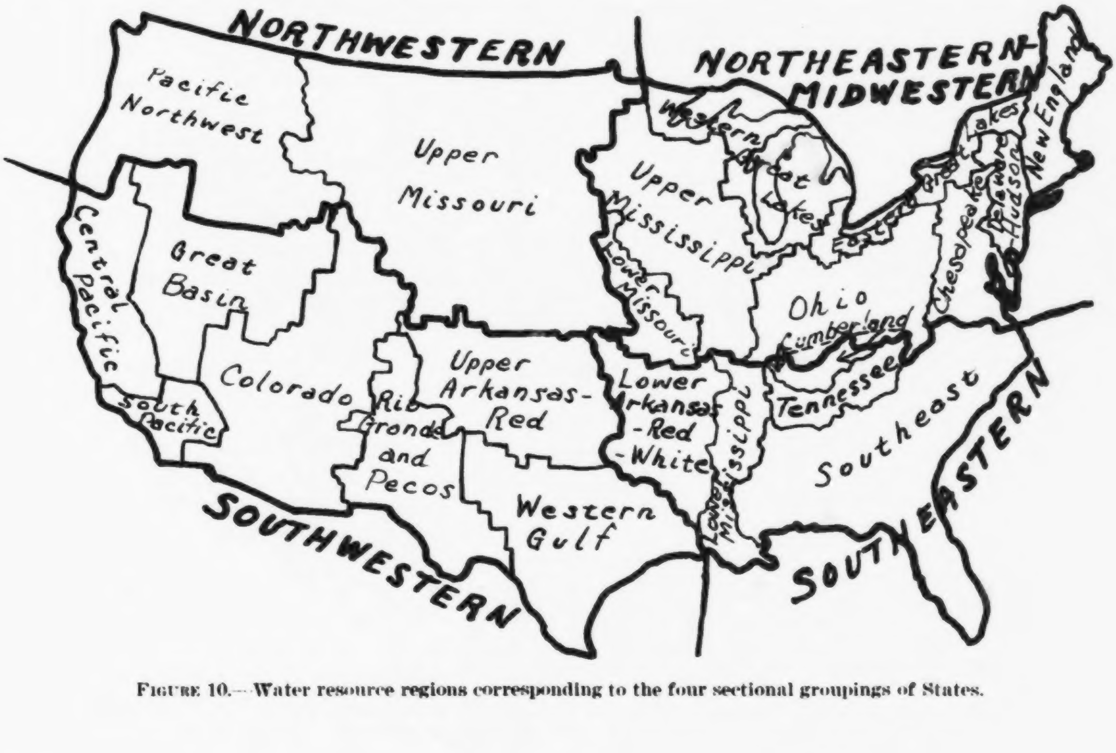
NORTHWESTERN
NORTHEASTERN-MIDWESTERN
SOUTHWESTERN
SOUTHEASTERN
Pacific Northwest
Upper Missouri
Central Pacific
Great Basin
South Pacific
Colorado
Rio Grande and Pecos
Upper Arkansas-Red
Western Gulf
Western Great Lakes
Upper Mississippi
Lower Missouri
Lower Arkansas-Red-White
Lower Mississippi
Ohio
Cumberland
Tennessee
Southeast
Eastern Great Lakes
Chesapeake
Delaware
Hudson
New England

FIGURE 10.—Water resource regions corresponding to the four sectional groupings of States.

water-control structures that detract from or interfere with economies of scale in basin development.

Encumbrance by other uses has most visibly grown in the northeastern-midwestern urban area, where stream valleys have been corridors for easy communication, and also have been attractive for residential, commercial, and industrial land use. Once established, such uses may become impossibly expensive to relocate when reservoir use of the site may be badly needed. A number of basins, but still a minority, have become seriously handicapped for development by such encumbrance. The Ohio Valley is probably our most affected in this respect, and the Connecticut and Merrimack are other examples. But the accelerating pace of economic growth faces the Nation with the necessity of recognizing the problem, or paying dearly in the future for ignoring it.

Another type of encumbrance, construction of inefficient water-control structures, has occurred sporadically, and can occur anywhere. Particularly under an economic system like our own, conflicts in objectives may arise as to the way in which a site is to be used. The manner of development best suited to immediate local needs may forestall the achievement of substantial later benefits in basinwide development. This was the basic technical issue in the now famous Hells Canyon case on the Columbia River, where the immediate best interest of the Idaho Power Co. was not compatible with the national long run interest in economies of scale.[59] The contrast in benefit for the two forms of development on the Hells Canyon site was not extreme, but it did illustrate a situation in which large differences are possible.

One form of encumbrance by inefficient structures is the presence of obsolete works, designed with the technology and for the service needs of a past day. They are encountered on the streams in any of the longer-settled sections of the country. In the case of inefficiently used hydroelectric power sites which fall under Federal Power Commission jurisdiction, the Commission may and does require redevelopment as license renewals are sought.

Some site protection has been attained through the Federal Water Power Acts of 1920 and 1935, through the Flood Control Act of 1938 (and subsequent acts), and through past Federal construction, which has been a real effort to obtain efficient site use.[59a] At the same time little administrative provision exists to forestall encumbrance of sites by other land uses, an important future problem. It is one of applying zoning, purchase, or other techniques of controlling land use to the preservation of unique and good sites for future valuable use. Foresighted State highway programs, like that of California, now have policies of acquiring rights-of-way for future highways years in advance of construction, at great savings. A similar policy for valuable storage and damsites might be equally appropriate.

Fundamental research in related scientific disciplines

A large and highly significant effort toward extending and improving the quality of fundamental research already exists under the supervision and support of the Federal Government. The operating research staffs of the great departments like Agriculture, Interior, or Health, Education, and Welfare, and the grant and contract programs of the National Science Foundation, the Department of Defense, and other agencies represent an aggregation of scientific resources whose scope is known by few Americans. It is therefore assumed that the committee does not require proof or general argument in this day as to the absolute necessity of fundamental scientific research to the future health of the Nation.

The question here is instead specialized. Does our present scientific effort contain the balance of disciplinary attention needed to assure rapid or even adequate progress in future comprehensive development? Or are we making adequate scientific preparation for water development to keep pace with the rapid technical and economic development of the future? A definite answer to these questions must await a detailed review of the actual situation, but the status of support and effort in several fields suggests the direction of possible program expansion. Additional attention to such subjects as cloud physics, the physics of terrestrial radiation, dynamic meteorology, the elements of prognostic hydrology, operations analysis of hydraulic systems, the hydrology of aquifers, plant genetics, plant physiology, the physical chemistry of water and water solutions, sedimentation phenomena, and a few other fields warrants serious study in planning future comprehensive development.

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[59] J. Krutilla and O. Eckstein, "Multiple-Purpose River Basin Development," Baltimore, 1958. See also Ackerman and Löf, op. cit., p. 475 ff.

[59a] Federal policy and lack of detailed economic analysis may have prevented the attainment of optimum site use in some cases, as in the Missouri Basin. Nevertheless good use of sites has been and is a principle of Federal project planning.

Collection and interpretation of basic data

Fundamental research and basic data collection not infrequently have been confused in policy, plan, and program. Fundamental research examines subjects of general scope, like the electrical properties of a raindrop. Basic data are those which describe actual events in the entire hydrologic cycle as they are observed from place to place on, above, or beneath the earth's surface. From fundamental research will come the leads toward improved techniques of comprehensive development; basic data are the immediate foundation for the actual planning of specific development programs, and for the operation of facilities, once they are constructed.

The outlines of much of the basic data problem now are well defined, particularly in the excellent study by Hoyt and Langbein.[60] As these experts have observed, there are still serious regional and local deficiencies in both coverage and strategy of collection and interpretation.

The importance of overcoming present deficiencies cannot be overstressed, for the demands of the future will be even more exacting. Indeed, as comprehensive development takes shape a number of new basic data problems will automatically appear. The more complex the sources of efficiency in development, the more dependent efficiency is on accurate basic data of adequate coverage.

Stated in general terms, an adequate basic data policy in the future should prepare the ground for full realization of the economies of scale through integrated multiple-purpose regulation of streams; it should permit the drafting of efficient long-range plans of ground water exploitation; it should provide for projections of precipitation cycles; it should provide for adequate and foresighted monitoring of water quality (including turbidity); it should provide inventories of unused supplies; and it should anticipate the application of comprehensive development, as defined in this report. It is not too much to expect that an accurate water budget, or a usable model therefor, should be at hand eventually for every major basin and for all tributaries in the country. An important obstacle at present is an understanding of the course of evapotranspiration and its measurement.

All this must take account of expenditure, because appropriations for this purpose will be limited. However, a budget increase over the present would bring gain to the basic data program. But the techniques of modern statistics and mathematical analysis also should be of much aid in taking steps toward the ends described above, within any reasonable budget. The important beginning is the clarification of basic data objectives in policy statement.

Experiment with innovations in development procedure

As a nerve center for stimulating research, as the principal "entrepreneur" for large-scale water control, and in several other vital roles, the Federal Government has a significant responsibility for timely experiment with innovations in technique, in administrative organization, and other new departures which can improve the efficiency of development and management. Within their statutory responsibilities the executive branch agencies of course have experimented, and do experiment, with the application of new techniques which may improve their operations. As mechanical engineering in the country progresses—or plant breeding, or statistical design, or other technical fields—innovations are appraised within the agencies and applied where usable. The past use of the latest earthmoving equipment, prestressed concrete, computer analysis, etc., furnishes examples of the action taken within this framework. The effectiveness of the existing procedure for the statutory programs will not be reviewed here. Its accomplishments have been real, even if its responses at times have been very deliberate.

The problems for the future in this area are of two sorts. The first is that of assuring forehanded conduct of pilot experiment in fields out of the traditional course of development. The Congress already has had some experience with this in the progress of the saline water conversion program. If the pattern of comprehensive development is accepted for the future, initiative will be needed in some new fields, and technical decisions must be made as to the relative values of and priorities for experiment among these. Again, prospective appropriations must be considered limited for these purposes. In other words, a technically coordinated view of the components of comprehensive development will be needed by the Congress. It is not now available. Some of the questions which may merit consideration later are experiment with operations analysis on an actual basin development, experiment with nuclear explosives, experiment with new ground water exploitation techniques, experiment with weather modification, sediment control, and other subjects ready for pilot study. (See table 4, last column.) Technical judgments will be needed to weigh the value of popular interest, and to move surely and efficiently in the future technologic environment.

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[60] W. Langbein and W. G. Hoyt, "Water Facts for the Nation's Future," Conservation Foundation, New York, 1959.

The second problem is that of experiment in administrative organization. Since the establishment of the TVA, there has been singularly little disposition to conduct experiments in this field. The interagency river basin committees and their related units have been the lone experiment of significance carried out in the twenty-seven years since 1933. Although it may be contended that this was enough experiment, the record is hardly one of imagination and disposition to examine alternatives. These qualities will be needed in the future, as the technical complexity of water development grows, and as competitive requirements for water increase. Technologic change sooner or later demands administrative adjustment as the history of industrial companies, or of the Department of Defense, well illustrates. Efficiency in future water development is not likely to be attained without conscious provision for experiment in such adjustment. The suggestions made for such experiment in the Delaware River Basin furnish an interesting fresh approach.[61] The encouragement of other experiments elsewhere might well profit the Nation.

Evaluating progress and reviewing experience

The author has stated elsewhere that "the past can crystallize a mold unsuited to present or future if a vigorous policy of review is not followed." [62] The complement of experimentation with innovation certainly is the feedback obtained by continued technical review of programs. The recognition of anachronisms and obsolescent procedure may be much aided in this way. Most of the major Federal agencies responsible for water development and management do have provision for such intraagency review, as in the Engineer Inspector General of the Corps of Engineers, the Technical Review Staff, and the Division of Management Research of the Department of the Interior, and other units. The adequacy of these activities is neither endorsed nor questioned here.

On the other hand, the provision for what might be called superdepartmental review does merit critical examination. Aside from Congressional investigation, such review has been afforded in the past by temporary commissions,[63] by the Bureau of the Budget, and more recently by the Office of the Public Works Coordinator in the White House. The technical staffs of both the latter two agencies, while competent, have been small. In practice the Federal Government in recent years has tended to discharge this function mainly by assigning responsibility periodically to a temporary agency. The feedback connection to the operating programs thus has been a sporadic one. Continuance of the present review policy into a future pattern of comprehensive development would certainly leave inadequate coverage for one important step toward efficiency. Expanded provision for technical review of programs on an interdepartmental level certainly merits policy consideration in preparation for the exacting requirements of comprehensive development.

The choice of Federal functions

True comprehensive water development, which the future will require, is a far more complex planning, entrepreneurial, and management task than anything yet undertaken within the United States. Furthermore, the rate of future development must be at a pace far in excess of any previous experience, within a national technologic environment changing at a rate beyond anything previously known. Finally, development must be accomplished within our Federal system of States, considering also the place of private enterprise and myriad local jurisdictions. Indeed, some essential functions in development can be exercised only by State or local agencies, public and private.

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[61] Syracuse University Research Group, "The Problem of Water Resources Administration, With Special Reference to the Delaware River Basin," a report submitted to the Water Research Foundation for the Delaware River Basin, 1959, 505 pages.

[62] Ackerman and Lof, op. cit., p. 525.

[63] E.g., First (1949) and Second (1955) Commission on the Organization of the Executive Branch, the President's Water Resources Policy Commission (1950), the President's Advisory Committee on Public Works (1956), and others.

This is a situation in which technical leadership will be required as never before—not only leadership, but the means of reaching thousands of decisions in timely manner, with common consent. Considering the increasing burdens which may be expected to fall on the Congress from other quarters, and the responsibility that rests on the Congress for many water development decisions, choice of Federal functions becomes a pertinent question for policy review. At one extreme the national organization may be geared to decide upon all but a few steps in development; at the other it could assume only a few constitutionally unavoidable responsibilities. The latter course clearly would provide no source of leadership, and appears already to have been discarded by the Congress in all post-1933 policy. The accretion of all possible functions under the Federal tent also has its dangers; it is possible to lose the essential qualities and conditions of progressive leadership in the midst of pressure for decisions on everything. The exercise of too many responsibilities by the Federal Establishment may be just as discouraging to efficient development as too few. This problem, then, may be stated thus: what functions in development must the Federal Government perform in order to meet the exacting technical and economic requirements of efficient national water development between 1960 and 2000?

Knowledge of a few background conditions may be helpful in reaching an answer to this question.

(*a*) Where multistate cooperative action in the past has been the only alternative to Federal responsibility, Federal action clearly has been less cumbersome, more responsive, and more efficient. Basinwide stream regulation for much of the country must depend on one of the two approaches.

(*b*) Because of the high degree of specialization required, leadership for and coordination of research, pilot-plant experiment, and other technical activities can be efficiently discharged by the Federal Establishment. Strategic private research and experiment also can be effectively stimulated by Federal encouragement.

(*c*) The most careful decisions about establishing facilities for direct local use of water services, like irrigation or electricity, are made where local bodies assume a major part of financial responsibility for the enterprise. The future risks of obsolescence on one hand, and the multiplication of local pressures for development on the other, together create a situation in which careful decisions on direct use will be financially important to the nation.

(*d*) The legal regulation of direct use, or allocation, of water and water services rests primarily with State jurisdictions. Federal activities have generated a gradually growing uncertainty and uneasiness about the water management pattern of the future within these jurisdictions, particularly in the Western States of prior appropriation law. Reaffirmation of state control of water allocation in particular is sought.[6]

The above are only illustrative of the factors to be considered in answering the question as to essential future Federal water development functions. Other important factors must also be entered, like the anticipated work load of congressional committees as related to the physical limits of committee members' capacities for review. These points, however, do suggest that not only the *extent* of Federal participation in future development should be reviewed, but also the *type of function*. It is highly probable that choice of function will have an important bearing on future efficiency.

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[6] See select committee hearings transcripts, Boise, Idaho, October 13; Denver, Colo., November 20; Albuquerque, N. Mex., November 23; and Salt Lake City, Utah, November 24, 1959.

VII. Suggestions for a Policy Encouraging Future Development Efficiency

Recognizing the national water requirements which must be met between 1960–2000, Federal leadership toward efficient development and use is vital. That leadership will be most effective if it is conducted so as to: (*a*) provide basic sources of water and water services in advance of actual needs; (*b*) plan and develop in a manner which takes advantage of scale economies; (*c*) promote an alert and imaginative pattern of experiment with technical innovation; (*d*) provide alert and flexible administrative responses to technical opportunities, with openings for administrative experiment as needed; and (*e*) concentrate on strategic functions, with Federal decisions on the potentially myriad local facilities and activities kept to the feasible minimum.

The following suggestions for a Federal Government policy directed toward these ends are submitted.

1. ESTABLISH A NATIONAL PROCEDURE OF COMPREHENSIVE DEVELOPMENT

Establish comprehensive development, along the general lines herein defined, as the procedural pattern for future Federal action in water resource development.

It would be recognized that the full range of techniques composing such a pattern is not immediately applicable to a majority of the country's river basins. However, policy should now reflect the fact that during this century water management will have to be viewed publicly as a much more highly organized procedure than it now is.

Comprehensive development *is* immediately applicable to the nine Southwestern States, and can offer valuable planning aids in meeting the problems of the northeastern-midwestern urban zone, the Southeast, and the Northwestern States.

2. COMPLETE BASIC WATER CONTROL SYSTEMS

Make the creation or completion of integrated basinwide water regulation systems a primary objective of Federal activity on all streams where physical conditions and the legally determined Federal interest make such regulation appropriate.

This policy would have the premise that full regulation of nearly all the Nation's streams is inescapable over the long run, and that substantial progress toward this end will have to be made during this century. Whatever the ultimate uses of water, regulation will be required, and a basic system can be adapted to serve most purposes.

Plans for a stream regulation program, of course, cannot separate regulation entirely from the purposes it serves. However, we previously have thought of our stream development programs *first* in terms of purposes—irrigation, navigation, etc.—regulation being designed to suit these purposes. It is now suggested that the future warrants some change in this procedure. We may now do best to *begin* our planning in terms of progress toward full regulation, making it the basic Federal program.

This course is suggested in the belief that a basic water control system in each basin is at least as important a part of the national productive plant as the National System of Defense and Interstate Highways. This highway system has been designed without knowing *exactly* what ends it will serve. It has sufficed that a given volume of traffic between given terminals be anticipated. The evolution of future activities and land use at terminals and interchanges is a matter which cannot be charted accurately as yet. Nevertheless, the basic need of the expressway system generally is accepted and construction is underway. The basic water control system may be justified with equal merit. The Nation should be ready to provide the water in a flexible system of regulation, even though we cannot forecast the exact future end use. Although the analog to the expressway can be overdrawn, we should plan for an interstate system of water regulation.

By full regulation we mean the construction of surface and subsurface storage facilities for periodically and seasonally fluctuating runoff, so as to provide within a given basin the maximum feasible amount of water releasable on a stable annual basis, on demand.[65]

Because they are so often based on stream channels, navigation channels should be considered a part of such regulation. Hydroelectric power generating facilities at storage dams also are a part, for similar reasons.

Commitment to a program of progress toward full regulation again is of particular immediate importance for the West, where another serious drought is very likely to occur during the remainder of the century. Such progress, however, can be strategic to the development of every region if construction is *carefully geared to anticipate economic growth prospects*, but planning is undertaken with the complete basin system in view. It can be the best means of assuring that economies of scale are taken advantage of in water development.

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[65] Theoretically defined, full regulation would be that where regulated flow is equal to the mean natural flow of an indefinitely long period. Regulation would be defined as "the amount of water that is stored or released from storage in * * * a year." (Langbein, op. cit., p. 1.) Actual regulation can never reach such a point because there are no methods of calculating such a mean, and the means of even very long periods may vary from one period to the next. (Leopold, "Water Yield and Reservoir Storage in the United States," Geological Survey Circular 410, p. 14.) Practical limits to full regulation also are set by evaporation and other storage losses. In practice full regulation as defined above may be approached where usable storage capacity is equal to about 2.5 to 4 years cumulative flow. (Langbein, op. cit., p. 4.) In practice also economic limits to storage will undoubtedly be reached before physical full regulation is attained because the last increments of storage will be extremely expensive. Hence the inclusion of "feasible" in the text definition.

3. SIMPLIFY THE FEDERAL PROGRAM CONCERNED WITH DIRECT USE

If a nationwide program of full regulation of streams is accepted as a basic point in Federal policy, a question follows as to how far beyond the construction of basic water control systems the Federal Government should go in actual construction. Clues may be sought in the shortcomings of present policy if it is continued into the future. Present policy includes Federal construction of storage works, navigation channels, and the hydrogenerating facilities which are part of a basic regulation system. It also includes entrepreneurship for and construction of large- and medium-sized irrigation distribution systems, local flood prevention and drainage works, grants for water quality improvement, and the maintenance of certain fish and wildlife services. If consistency prevails, almost certainly Congress must decide in the future on Federal entrepreneurship for primary water delivery systems to industrial and urban areas, and water recreation facilities. Such entrepreneurship could be construed as a logical extension of present policy.

The following shortcomings of such a policy, as extended or as it is, may be listed.

(*a*) It makes the Federal program a confusing (and at times contradictory) mass of detail, in which the important objective of establishing basic systems of water control is obscured by a number of local direct-use projects, economically tied to the basic regulation works. In the more rapidly moving, more complicated technical and economic environment of the future the confusion can become compounded, and true popular understanding of a regulation program can become impossible.

(*b*) It concentrates many more entrepreneurial decisions on the Federal establishment than necessary.

(*c*) It removes many decisions on financial feasibility from the places where they will be made most carefully—that is, in the project locality or region. Hence it increases the risk of losses from obsolescence.

(*d*) Federal procedure has always had difficulty in adapting to small project entrepreneurship. In addition, as previously noted, Federal procedure has had difficulty with planning multipurpose use in some tributary basins.

(*e*) It continues to confuse and obscure the spheres of natural interest and responsibility on the part of Federal Government on one hand, and States, municipalities, and other local bodies on the other hand. If there is concern and misunderstanding already within the States on this score, it will be intensified in the future. Many of the actions which comprehensive development ultimately will depend on are clearly non-Federal responsibilities, starting with water allocation.

The above shortcomings may be at least partly avoided, and development efficiency served, if the Federal Government clearly distinguishes direct-use projects as primarily for the entrepreneurship of States, municipalities, local public bodies, and private enterprise. Included among such works would be all irrigation pumping and water distribution facilities, local flood prevention and drainage, water quality improvement facilities, water distribution to municipalities, rural water districts, and industrial districts, single-purpose hydroelectric powerplants,[66] and water recreation facilities.

This does not necessarily mean the withdrawal of Federal or congressional interest, should there be social or other reasons for stimulating development of direct-use projects, as in the past. For example, Congress might decide that the national interest demanded immediate creation of more family farms, and that new irrigation was a means of accomplishing this. Or it might see the need for extending domestic water system coverage into rural residential areas. Could the national interest be so served, and the responsibility be discharged with this policy?

A second question—would worthy local projects be retarded for lack of financing? This has been a major reason for past Federal entrepreneurship, particularly for irrigation and flood control.

Both questions may be answered satisfactorily through Federal grant and loan participation, even as pollution control is being met now in this way. It is suggested that a development loan fund to provide low interest loans could be a central instrument in such a policy. The practicality of such an instrument has been well proven by the Rural Electrification loans, and other experience. Where social or other objectives are determined by the Congress not to be adequately served by low interest loans, grants-in-aid are a supplementary instrument which can be used effectively to obtain action. Thus the national interest can be expressed and safeguarded even if entrepreneurship for direct-use projects is, by policy, primarily non-Federal.

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[66] The author recognizes that hydroelectric generating facilities at multiple-purpose storage dams are "direct-use" projects; these and navigation channels are the chief exceptions to the policy principle, suggested above in that they are clearly appropriate for Federal entrepreneurship.

4. DEVELOP STRATEGY FOR THE GROWTH AND APPLICATION OF TECHNICAL IMPROVEMENT [67]

Recognize that the quality, amount, and direction of fundamental scientific research in certain fields (e.g., cloud physics, prognostic hydrology, sedimentation, etc.) are *vital* to the progress of water development techniques, and that continuous attention profitably can be paid to the strategy of Federal encouragement or support of such research. Recognize further that there also can be a strategy to experiment with the application of innovations within all of the comprehensive development techniques. The objectives would be the recognition of "growing points" in the advance of science and technology, and their application to water development. Finally, recognize that proven technical innovation in the future will open opportunity for, and perhaps even require, experiment in administrative management of water supply, in cooperation with the States and other bodies.

5. MODERNIZE AND EXPAND BASIC DATA COLLECTION AND INTERPRETATION [68]

Recognize the need for modernizing and expanding basic data collection in a manner which will serve adequately the future requirements of comprehensive development.

6. PROTECT ESSENTIAL STORAGE AND DAM SITES [69]

Establish the means for protecting from encumbrance, storage, dam, and other sites for future works which are adjudged to be essential to full regulation of interstate streams, or adjudged otherwise necessary to a program of comprehensive development. Establish at the same time means for making such sites available for timely use.

7. RECOGNIZE THE INFLUENCE OF FUTURE URBAN REQUIREMENTS [70]

Recognize the future dominant importance of meeting urban and industrial requirements in planning the progress of the national water development program. Encourage among all Federal agencies administrative adjustments which will promote a sensitivity to urban problems in program and project planning, including those of dispersed residence and industry. Particular attention should be paid to the further development of navigation in the northeastern-midwestern urban zone.

8. RECOGNIZE THE OPPORTUNITY FOR RELATED ECONOMIES OF SCALE [71]

Recognize that there is substantial opportunity for further consumer benefit through economies of scale in services related to water, particularly in electricity generation and distribution. Encourage a legal and economic environment which will favor response to these opportunities by all responsible entrepreneurs, public and private.

POLICY IMPLEMENTATION

Means of implementation are important factors in decisions upon the feasibility of any policy. The opportunity for building upon existing administrative and legal structure, the risk of disruptive loss in time and purpose, the likely availability of new specialized personnel and facilities—these and other similar factors must be weighed in judging a policy departure. The elements of policy suggested above may be divided into two groups: (a) those which can be implemented readily within the existing legal and administrative structure, wholly or in large part; and (*b*) those which best can be implemented deliberately over a period of years, as determined through accompanying special study. It is thought that both could be carried out within the existing structure, or by building upon it. Should it be the will of Congress, all policy change can be carried out gradually enough to be easily assimilated within the present administrative pattern.

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[67] See sec. VI, pp. 43-44, for background discussion.

[68] See sec. VI, pp. 43-44, for background discussion.

[69] See sec. VI, pp. 42-43, for background discussion.

[70] Background discussions, pp. 1-4 and app. 1.

[71] Background discussions, pp. 35-36 and app. 9.

Policy elements which could be implemented readily

The following suggested points of policy could be implemented readily, and in the manner indicated.

(1) *Planning and construction of basic water control systems.*—(*a*) Instructions to existing construction agencies, by congressional resolution or otherwise; (*b*) appropriation of funds for planning as needed; and (*c*) program authorization and appropriations for construction in the usual manner.

(2) *Basic data collection and interpretation.*—(*a*) Instructions to existing data collection agencies, like the Geological Survey, the Weather Bureau, and others; and (*b*) appropriations to support experiment and expanded coverage.

(3) *Protection of essential storage and dam sites.*—(*a*) Instructions to the Interagency Committee on Water Resources, with supplementary instructions for cooperative support by the participating statutory agencies; (*b*) authorization of needed negotiation by the ICWR or its agency representative with State or other governmental jurisdiction; (*c*) appropriation of a fund to be used for site protection or reservation purposes; and (*d*) any needed legislative action for protection or reservation. For example, legislative sanction may be needed for the ICWR, in addition to the existing executive sanction.

(4) *Recognition of the influence of future urban requirements.*—Instructions to existing Federal agencies with statutory responsibilities for planning water development and management programs. They would include the Corps of Engineers, the Department of the Interior, the Soil Conservation Service, the Forest Service, and others.

Policy elements best implemented deliberately

The remaining four suggested points of policy will require careful and specialized study, and evolution over time in the light of that study. These are the establishment of comprehensive development, simplifying the Federal program concerned with direct water use, a strategy for technical improvement, and encouraging the employment of related economies of scale. The following first steps toward implementation of these elements might be considered:

(1) Appointment of a small professional advisory staff of limited but adequately long tenure under the joint sponsorship of the Senate (or Senate and House) Committees of Public Works, Commerce, Agriculture, and Interior, with directives to: (*a*) study thoroughly the techniques of comprehensive development, with view toward Federal leadership in establishing a pattern of comprehensive water development as standard future procedure; (*b*) recommend strategic technical, administrative, legislative, negotiative, and other action necessary to establish comprehensive development procedure; (*c*) recommend the timing, direction, and extent of support for fundamental scientific research which the Federal Government should encourage so as to promote efficient water development; (*d*) recommend the methods and instruments of permanent technical coordination and review of Federal-State-local operations in comprehensive development; (*e*) prepare for needed joint deliberations by the Senate (or Senate and House) committees on the above subjects; (*f*) recommend procedure for creating the regional water development study commissions suggested in (4) below.

(2) Request the President establish a small temporary advisory staff in the executive branch, to cooperate with the congressional advisory staff as needed, in carrying out the responsibilities suggested in (1) above.

(3) Request the President, after executive branch study of the simplification of Federal participation in direct-use water projects, to recommend to the Congress: (*a*) procedures for Federal-State-local coordination in subsequent development; and (*b*) the means of expressing the national interest in such works, as appropriate.

(4) Request the President for executive branch study of the national opportunities for taking further advantage of economies of scale in electric power generation and distribution, and other water-related services. The study might be conducted in consultation with the Department of the Interior, the Securities and Exchange Commission, the Attorney General, the Federal Power Commission, the Tennessee Valley Authority, representatives of the Nation's private utilities and such other agencies as may be deemed appropriate by the President. Recommendations would be made to the Congress for future Federal action which could promote such economies, and comment would be made on the opportunities open to other levels of jurisdiction in these fields.

(5) Creation of two regional water development

study commissions of temporary tenure, one for the nine Southwestern States, and the other for the States of the northeastern-midwestern urban area, with these responsibilities: (*a*) study of the possibilities of applying comprehensive development techniques within each region; (*b*) design of experimental programs for applying comprehensive development with recommendation for Federal participation in such experiment.

The timing of the creation and tenure of these commissions would be a subject for recommendation by the joint congressional committees' advisory staff on comprehensive development, as noted in (1)(*f*) above.

Value of the regional water development study commissions.—Whether or not the elements of policy suggested above are accepted and implemented, it is believed that official study of the water development problems and possible Federal program responses in the southwestern region and in the northeastern-midwestern regions can provide extremely valuable background data for future Federal planning and project authorizations. These two great regions, as noted earlier, will provide the tests for success on any policy, including a continuation of the old policies. Although there are many variations within each of these regions, in each case they exhibit enough similarity in basic planning problems so that overall study can provide profitable clues in judging future national interest.

POSSIBLE NATIONAL BENEFITS FROM SOME POLICY CHANGES

The policy suggestions presented above have been offered in the belief that they have the following attributes:

(1) They will enable substantial gains in efficiency for national water development. They should be a vigorous beginning toward providing the optimum combination of employment, income level, and public services derivable from the water made available in the several States by the levels of total expenditure chosen by the public through its representatives.

(2) They will enable the Nation to make fuller use of its scientific and technical resources in future water development.

(3) They will permit a higher degree of flexibility in programing than present policy, thus affording more timely adjustment to the rapidly moving technical environment of the future.

(4) They can meet at least several of the important general development problems which were identified in this report.

(5) They can simplify the burden of deliberation and decision on the part of Congress, while offering at the same time strategic means of promoting and directing development in the national interest.

(6) They suggest gradual future evolution of program within the existing administrative structure, rather than disrupting major changes of administrative responsibility.

(7) They provide an opportunity for a more clear division of activities between Federal and non-Federal jurisdictions and agencies.

In addition to domestic benefits, the possible influence of domestic technology upon foreign policy must also be considered.

As long as the United States is concerned with economic development in foreign countries, techniques of meeting water requirements can be important instruments of policy. It is safe to say that the development of water resources is a strategic item in nearly every country possessing undeveloped resources and ambitions to obtain a higher level of living for its citizens.

The United States thus far has been in a preeminent position to use its water development techniques as an instrument of foreign economic policy, because of its technical advancement, its capacity to underwrite the needed investments, its varied past experience in the field, and the preoccupation of other foreign powers with their domestic requirements. The widespread foreign interest in the Tennessee Valley Authority, and the far-ranging activities of Federal agencies and American private consulting firms, have illustrated this Nation's favored position.

It would appear that the United States no longer occupies the same position of technical preeminence, considering the moves of the Soviet Union toward technical assistance,[72] their very boldly conceived interbasin multiple-purpose plans,[73] and their vast technical and engineering training programs. The observations made during the 1959 Senate field investigation of Soviet water development,[74] and other evidence in the press and technical journals, suggest the appearance of strong Soviet capacity to use water development as an instrument of foreign policy. Their technique is massive, spectacular, and eye-catching, but we are not yet certain of its versatility.

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[72] As in the case of the Aswan Dam, Egypt.

If the openings to apply our technology abroad concern the Congress, the means of creating a still more advanced technique in this country may be examined with profit. The better the scientific basis of this technique, and the broader the United States domestic experience with it, the more successful application abroad will be. It is believed that the policy suggestions offered herein may contribute to the evolution of an efficient and highly flexible technique of water development, applicable to a wide variety of foreign environments, as well as to our own. If so, it may be attractive to those who are politically responsible for foreign economic development. Here is an opportunity for the Nation to demonstrate its alertness to efficiency and advanced technique in a basic public enterprise of peaceful intent.

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[73] E.g., the Davydov plan for reversal of the Ob, Irtysh, and Yenisei Rivers, including the irrigation of 50 million acres in Turkestan, and other benefits; see A. Lebeda and B. Yakovlev, "Soviet Waterways," Munich, 1956, pp. 101-107. Also the great interbasin development embracing the Volga, Don, Kama, Pechora, Northern Dvina, and other rivers of European U.S.S.R.; see V. V. Zvonkov, "Integrated Water Resources Development in the River Basins of the U.S.S.R.," Moscow, 1957.

[74] 86th Cong., 1st sess., Relative Water and Power Resource Development in the U.S.S.R. and the U.S.A., report and staff studies to the Committees on Interior and Insular Affairs and Public Works, U.S. Senate, Washington, Jan. 4, 1960, 174 pages.

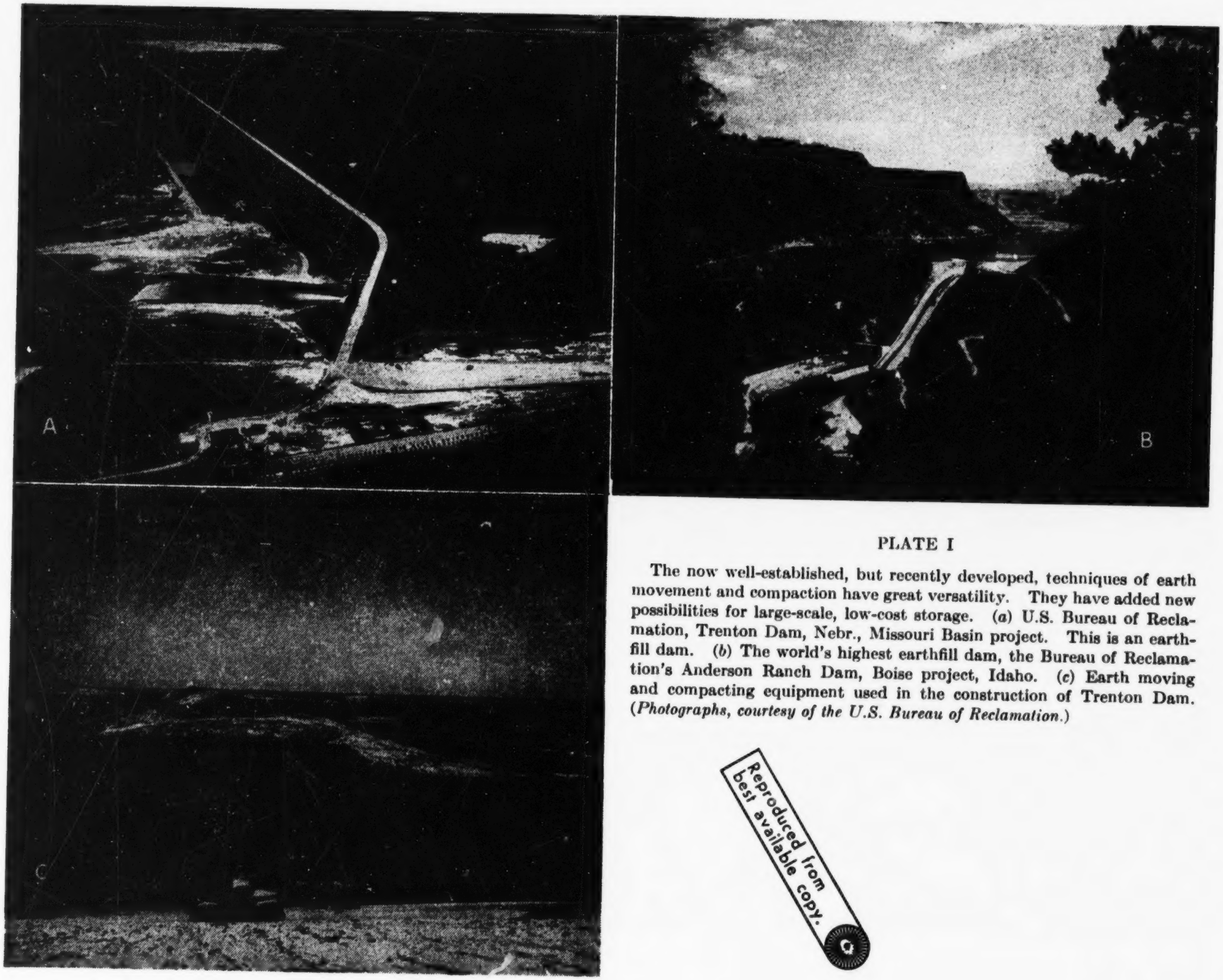

PLATE I

The now well-established, but recently developed, techniques of earth movement and compaction have great versatility. They have added new possibilities for large-scale, low-cost storage. (*a*) U.S. Bureau of Reclamation, Trenton Dam, Nebr., Missouri Basin project. This is an earthfill dam. (*b*) The world's highest earthfill dam, the Bureau of Reclamation's Anderson Ranch Dam, Boise project, Idaho. (*c*) Earth moving and compacting equipment used in the construction of Trenton Dam. (*Photographs, courtesy of the U.S. Bureau of Reclamation.*)

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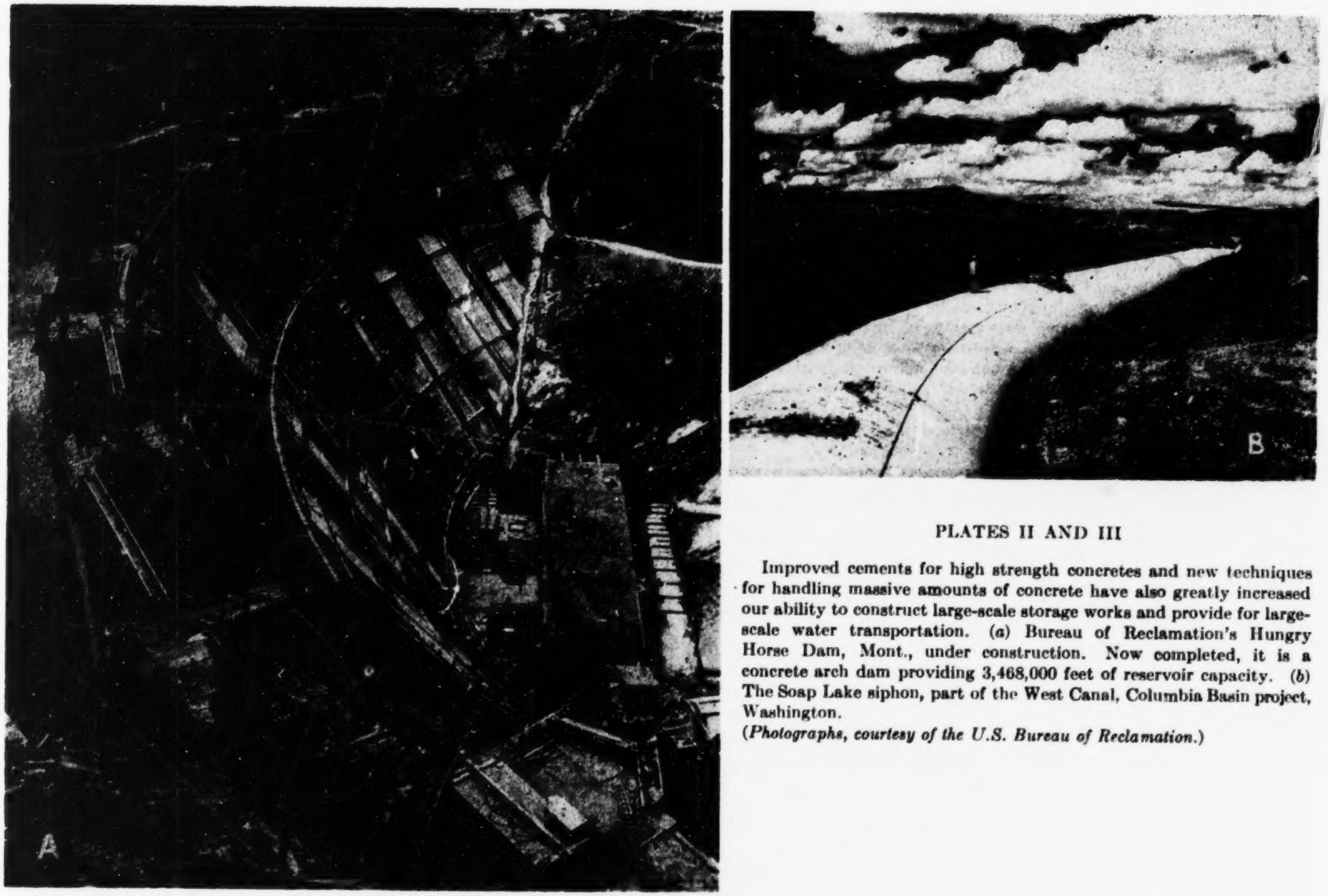

PLATES II AND III

Improved cements for high strength concretes and new techniques for handling massive amounts of concrete have also greatly increased our ability to construct large-scale storage works and provide for large-scale water transportation. (*a*) Bureau of Reclamation's Hungry Horse Dam, Mont., under construction. Now completed, it is a concrete arch dam providing 3,468,000 feet of reservoir capacity. (*b*) The Soap Lake siphon, part of the West Canal, Columbia Basin project, Washington.

(*Photographs, courtesy of the U.S. Bureau of Reclamation.*)

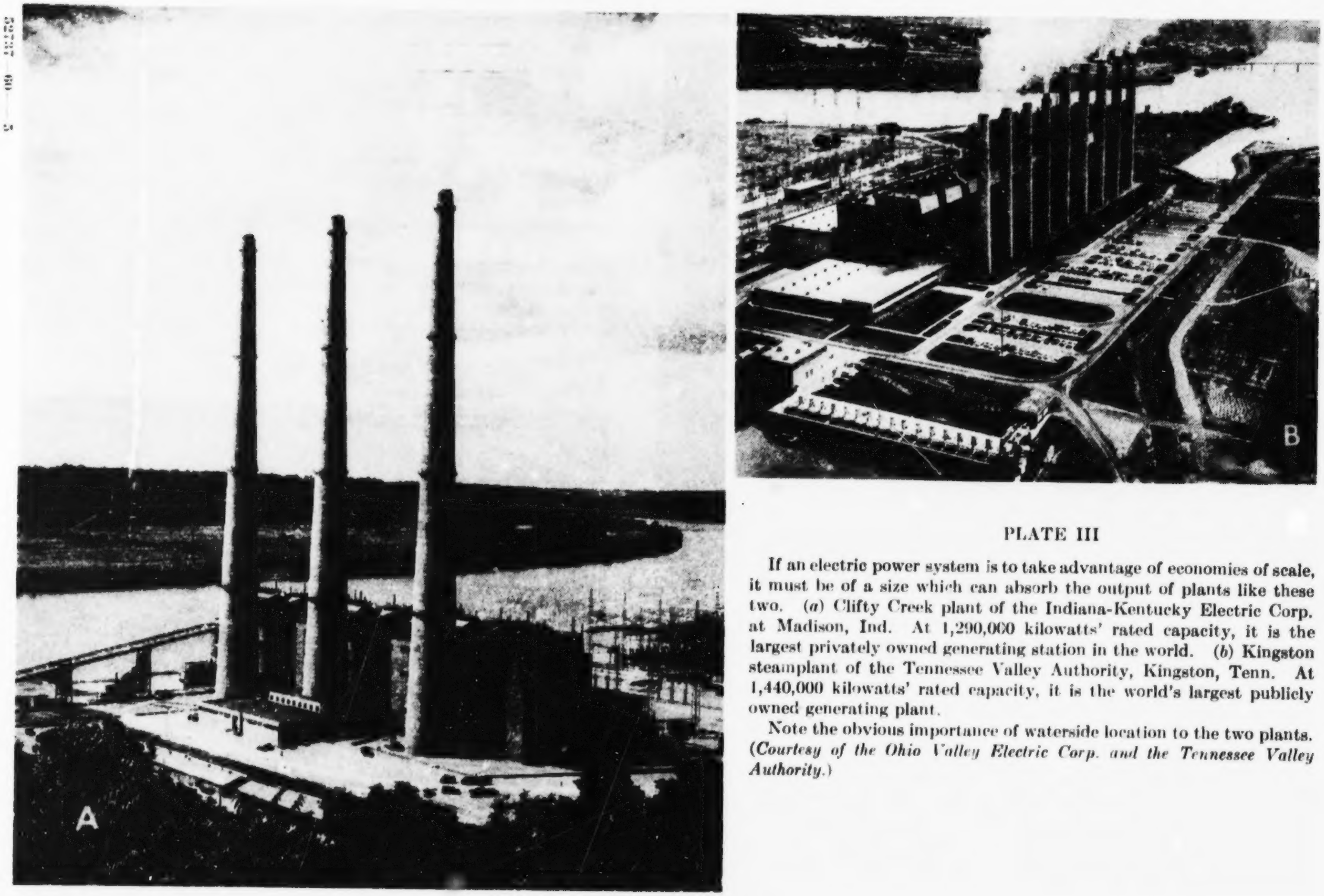

PLATE III

If an electric power system is to take advantage of economies of scale, it must be of a size which can absorb the output of plants like these two. (*a*) Clifty Creek plant of the Indiana-Kentucky Electric Corp. at Madison, Ind. At 1,290,000 kilowatts' rated capacity, it is the largest privately owned generating station in the world. (*b*) Kingston steamplant of the Tennessee Valley Authority, Kingston, Tenn. At 1,440,000 kilowatts' rated capacity, it is the world's largest publicly owned generating plant.

Note the obvious importance of waterside location to the two plants. (*Courtesy of the Ohio Valley Electric Corp. and the Tennessee Valley Authority.*)

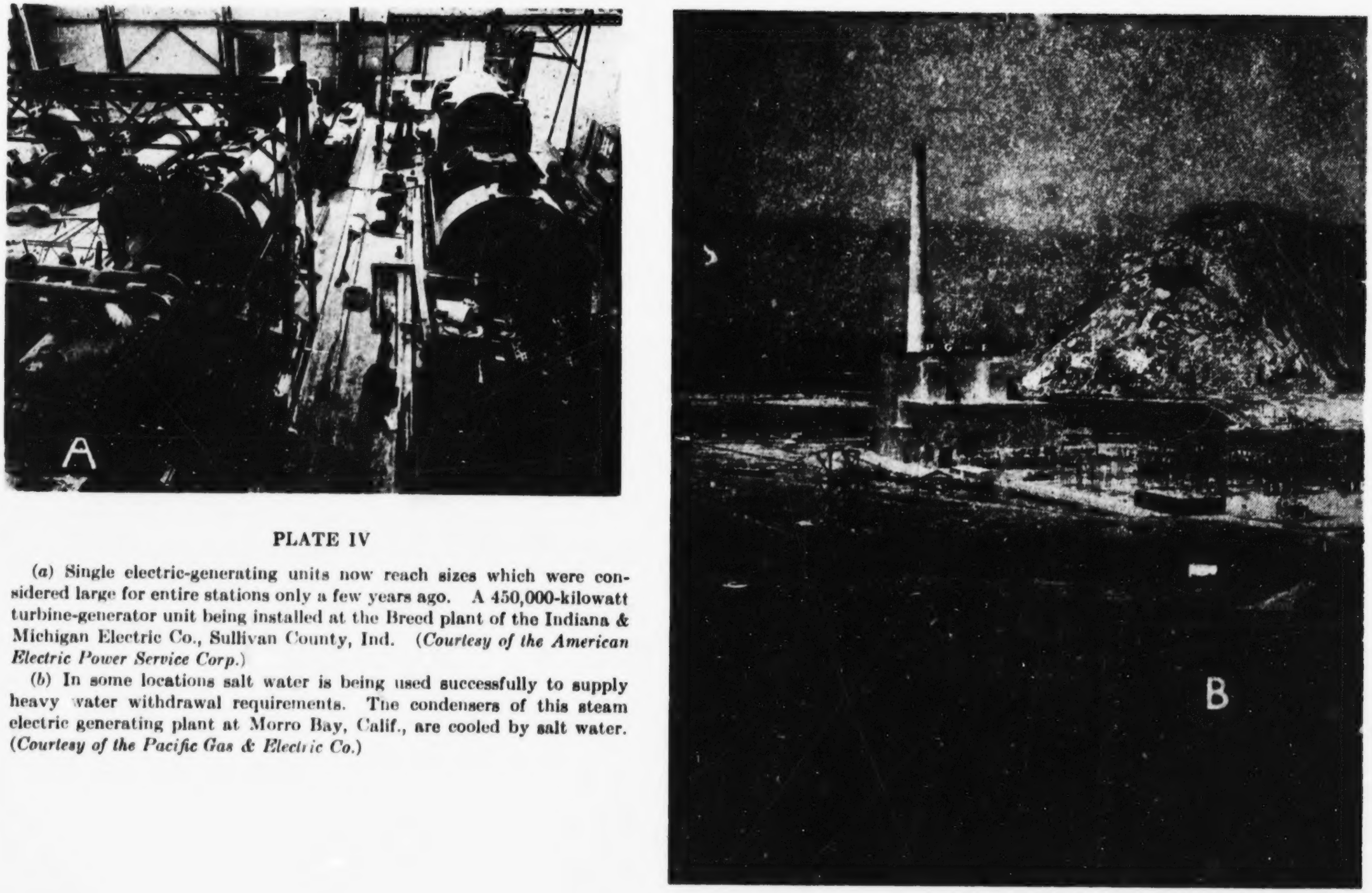

PLATE IV

(*a*) Single electric-generating units now reach sizes which were considered large for entire stations only a few years ago. A 450,000-kilowatt turbine-generator unit being installed at the Breed plant of the Indiana & Michigan Electric Co., Sullivan County, Ind. (*Courtesy of the American Electric Power Service Corp.*)

(*b*) In some locations salt water is being used successfully to supply heavy water withdrawal requirements. The condensers of this steam electric generating plant at Morro Bay, Calif., are cooled by salt water. (*Courtesy of the Pacific Gas & Electric Co.*)

APPENDIXES

Page

Appendix 1. Future urban growth in the United States 59

Appendix 2. Water resource planning and development in agriculture 62

Appendix 3. Brief description of systems analysis methods 63

Appendix 4. Report on the Harvard program of research in water resources development (excerpts) 64

Appendix 5. Synthetic hydrology and probability analysis 78

Appendix 6. Reasons for an economic analysis of weather modification 78

Appendix 7. Summary evaluation of known techniques for discovery and appraisal of ground-water deposits 80

Appendix 8. Water budgeting and irrigation 81

Appendix 9. Thermal-electric generation; correlation of efficiency with size of unit and size of plant 86

Appendix 10. The use of nuclear explosives in water resource development, by Donald Patton 87

Appendix 11. The applicability of comprehensive development to the water problems of the nine Southwestern States, 1960–2000 89

Figures in Appendixes

Figure A. Cost—Capacity function, storage dam 66

Figure B. Output—Capacity function, storage dam 67

Figure C. Cost—Output function, storage dam 67

Figure D. Gross benefit-output curve 68

Figure E. Two reservoir-single purpose system, iso-cost and iso-output functions 69

Figure F. Expected net benefit-scale of development function with confidence limits 71

Figure G. Prototype river basin system 72

Figure H. Map of Simple Valley 76

Figure I. Annual march of precipitation and potential evapotranspiration at Seabrook, N.J. (from Ackerman and Löf, op. cit., p. 446) 83

Figure J. Typical irrigation schedule in humid Eastern States (from Ackerman and Löf, op. cit., p. 449) 85

Figure K. Total production expenses (excluding fuel) of 100- and 200-megawatt thermal electric generating units compared to plant size, based on 8,000 hours' use, 1957 (Tennessee Valley Authority, Office of Power, 1959) 87

Figure L. Per capita water consumption from municipal systems, Denver, Colo., and Phoenix, Ariz. Sources: Statistical data from Phoenix Department of Water and Sewers, and city of Denver 91

Figure M. Hardness of surface and ground waters in the United States (from Ackerman and Löf, op. cit., p. 216) 93

Figure N. Some functions in the implementation of comprehensive development, as related to each other and to legislation 96

Tables in Appendixes

Table A. Objective functions 64

Table B. System units and outputs 70

Table C. Four estimates of stream runoff in Texas 89

Table D. Some basic data for evaluating water requirements in the Southwestern States, year 2000 90

Table E. Average annual runoff during driest 6-year period and driest 10-year period and runoff of driest single year between 1921 and 1959, as a percentage of normal runoff, nine Southwestern States 90

Table F. Estimated runoff in Texas, 1946–57, and cumulative departure of precipitation 92

Table G. Usable reservoir storage capacity, nine Southwestern States, January 1, 1954 92

Table H. A model of long-distance water transportation by conduit in Western United States 94

Appendix 1

Future Urban Growth in the United States[1]

DISTRIBUTION OF URBAN AREAS AND ANTICIPATED CITY GROWTH

The geographical distribution of urban functions and urban areas in the country is important in analyzing future urban growth. At present there would appear to be three types of urban area distribution. The most distinctive is the relatively dense concentration of urban areas in the northeastern-midwestern manufacturing belt. Within a northeastern-midwestern area containing only 8 percent of the country's land area there were, in 1950, 43 percent of the resident population of the Nation and 68 percent of the manufacturing employment, a pursuit we usually associate with urban areas. If we add to this 8 percent of the country's land area another 7 percent which is adjacent principally in Wisconsin, Missouri, and Iowa, the concentration of population and urban characteristics is even more striking. Within this 15 percent of area there were in 1950 more than half the total population of the country, nearly three-fourths of the total industrial employment, and nearly three-fifths of the total income of individuals.[2]

The outlook for prospective population growth within the several regions between now and 1980 is equally interesting geographically. It is one of increasing concentration within the northeastern-midwestern urban region with a noteworthy new concentration in California. A sample of the urban growth to be expected by 1980 shows a generally high rate of growth in the western Gulf States and California. However, about half of the total growth of the Nation's population between now and 1980 is expected within the 15 percent of the Nation's area. If the expected growth in California is added to the northern urban zone, two-thirds of the expected total growth is accounted for. California is expected to increase its population in this period by 70 percent to become the most populous State in the Union. If the growth of California, Texas, and Florida is added to that of the northern urban zone, nearly four-fifths of the Nation's expected population growth by 1980 is included. The population growth of the Nation, which will be entirely urban, then will also be concentrated regionally. Forty-five percent will be in 15 percent of the country's land area. More than half of the remainder will be in three States. If public programs are to be related to people's anticipated needs, and needs are in some part a function of numbers of people, these geographical facts would seem to be an elemental part of planning for the development of resources and public facilities.

The characteristics of the two most important regions of urban settlement in the future, the northeastern-midwestern and the Californian, are quite definite. Aside from the general density of settlement, the number of urban foci, the size of the supercities, and the concentration of manufacturing, these are also regions of high average land values, and they have a very large share of the Nation's total market potential. Half of the national market a few years ago was with the section of the northern urban region containing only 8 percent of the country's land area.[3] These regions, furthermore, are sections where spreading urban land use is tending to cause a degree of coalescence among the urban centers of each region. It has led one author to postulate a "megalopolis" extending from Boston to Washington on the Atlantic seaboard.[4] While field observation shows "megalopolis" to be something less than reality as yet, the fact remains that a number of individual metropolitan areas within the northern and the California regions are moving ever closer to each other in their suburban spread. It is also true that the local hinterland-city center relations are in a state of some confusion within many parts of the northern region.

In a sense these two giant urbanized regions may be viewed as eastern and western nodes in a Nation which we may now consider a single unit in its economic geography.

Elsewhere in the Nation we may think of two other large regions, as far as the characteristics of urban settlement are concerned. One is the Southeast, bounded roughly by the Ohio River line on the north and by the 98th meridian on the west. The other is the arid, semiarid, and montane West. Within the first, the more traditional relation of city and hinterland may be observed. While manufacturing has developed to some degree, particularly in Texas and along the Piedmont, the classic relation of commercial and administrative center and rural hinterland still is a dominant feature of the southeastern urban picture. The positions of Nashville, Knoxville, and Memphis, Tenn.; Lexington, Ky; Jackson, Miss.; Little Rock, Ark.; San Antonio, Tex.,[5] and others are illustrative. City-hinter-

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[1] Adapted, with permission of the Urban Land Institute, from the author's "The National Environment of Urban Growth and Highway Construction," Urban Land Institute Technical Bulletin 31, 1957.

[2] E. L. Ullman, "Regional Structure and Arrangement," Office of Naval Research Contract No. Nonr-477(03), Report No. 10, Seattle, 1954, p. 16. Even though it is only 15 percent of the land area of the United States, it is a large area, being equivalent to the combined areas of Great Britain, France, Italy, Belgium, Netherlands, and Switzerland.

[3] C. D. Harris, "The Market as a Factor in the Localization of Industry in the United States," Annals of the Association of American Geographers, vol. XLIV (1954), pp. 315-348, reference on p. 320.

[4] J. Gottman, "Megalopolis, or the Urbanization of the Northeastern Seaboard," Economic Geography, 33 (1957), pp. 189-200.

[5] Eastern Texas was included within the "Southeast" in the analysis which has been adapted for reproduction here. All of Texas, however, has been placed in the "Southwestern nine States" grouped for the text analysis of vol. 1 of this report.

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land relations still have a relatively stable pattern, in contrast to the northern urban region. At the same time there is a more or less continuous net of rural settlement throughout the region.

The western region is one which has what might be called an oasis type of urban location. In some places it is the presence of irrigation agriculture, as at Salt Lake City, or Phoenix, Ariz., which has prompted urban growth to serve the area. In others it is mineral deposits, as at Butte, Mont. In still others proximity to a mountain pass has been important, as at El Paso, or Spokane. The urban centers in this region are relatively few; they have definite hinterlands, somewhat isolated one from the other. The density of settlement is likely to remain thin in most of the region within the foreseeable future.

SUMMARY OF REGIONAL DIFFERENCES

The pattern of urban characteristics thus far depicted for the United States is one of increasingly urban residence and occupation, in cities which tend more and more toward multifunctional activities. Geographically, four roughly delineated regions may be discerned: (1) The northeastern-midwestern "supernode" with the densest concentration of urban settlement, urban employment, and, in places, coalescing urban areas. (2) Another "supernode" in process of formation in central and southern California. (3) A southeastern region with a more or less continuous net of rural settlement, in which the countryside still "sets up" central places. (4) A western region with a thin spotting of urban areas, dependent upon oasis, or oasislike economic activities.

Certain changes already have been forecast in this pattern, the forecast being based mainly on recent migration and other demographic and settlement trends. Thus, the growth of the Californian urban areas is taken for granted, as are major increases in the population of eastern Texas and Florida.

FUTURE INFLUENCE OF RESOURCE SUPPLY

With this background one should examine further possible changes in the economic geography, or the resource-sustenance pattern of the Nation.

The basic changes to be examined are those relating to the sources of materials and food which nourish the Nation's people and industries. Two likely changes which may illustrate considerations to be taken into account in planning are the sources of national minerals supply, and technical events important to regional agricultural and forestry production.

The United States has become increasingly dependent on foreign sources of minerals. Petroleum, which is as near a mineral trademark of the American culture as we have, was imported to the extent of about 12 percent of total consumption in 1955. Between 1940 and 1958 our position changed from one of exporting (net) about 46 million barrels of petroleum and petroleum products to one of importing (net) about 621 million barrels.[6] This change already has been reflected in substantial commitments of American petroleum companies to exploration and production abroad.

Other mineral-supply changes are illustrated by iron ore and aluminum. In 1959 about 25 percent of our iron ore was imported from abroad, with percentages likely to increase in the future. In 1940 only a little over 1 percent was imported. Nearly all of our fast rising consumption of aluminum, now about 2.1 million tons annually, is dependent on foreign bauxite or aluminum reduction. Foreign dependence on minerals used in lesser quantities shows a similar trend for all but a few, like sulfur, salt, and some alloy materials. The effects are illustrated in some growth of the steel industry on tidewater, and in the seaboard locations of major aluminum production facilities.

The almost certain growth of dependence on foreign sources of some important materials raises the question of accessibility to bulk transportation by water. In this the major recent change is the St. Lawrence Seaway, which has opened the western part of the northern urban region to something resembling tidewater connections. The future effects of the seaway already have been widely discussed, although charting the detail of these effects is far from complete, or agreed upon. It seems reasonably clear that the western end of the northern urban region at the very least will have a decidedly improved position in relation to foreign materials, and an improved position for the export of the manufactured goods now in demand to pay for those materials. This cannot help promoting the further urbanization of the western half of this urban region.

The seaway gives Great Lakes ports a position which requires a new appraisal of further development of the now very incomplete network of inland waterways in the Midwest and the Southeast. The feasibility and desirability of improved Lake Michigan-Mississippi River connections, and an Ohio River-Lake Erie waterway connection, may result in a new system of moving bulk materials, important to both the northern urban region and the Southeast. Hitherto the inland waterways have been too disconnected to be viewed as a system.

A second type of change to be considered in future planning is the regional effect of technical changes in agriculture, forestry, and forest-product utilization. They would appear to be destined for a major impact upon the Southeast. The forestry and forest utilization of this region already are in the process of transformation, consequent upon the technical improvement of processes for pulping southern pine species and hardwoods. The recent apparent economic feasibility of producing even newsprint from hardwood species introduces still another possibility for the industrial utilization of the southern woodland, and for a better-managed, more-productive resource.

Agricultural technology also would seem to point in the direction of major changes in the position of this region as an agricultural producer, as compared to the present and the recent past. The rapid growth of techniques of artificial fertilization and irrigation alone indicates that the Southeast is only at the beginning of a stage in which its agricultural productivity is certain to be much increased. The potential production of the lower Mississippi

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[6] U.S. Bureau of Mines, Mineral Industry Surveys.

Valley alluvial lands alone is sufficient to add substantially to the national agricultural output.

The position of the Southeast is further strengthened for the future in that it still has the major sites for promising future petroleum production in the offshore structures of the gulf coast. Finally it has the major lands suitable for subtropical agriculture (seasonal or annual). This is a significant consideration when one considers the demographically broad base of the improved standards of nutrition, the mounting population of the Nation, and the loss of subtropical agriculture lands in southern California to urban and suburban uses.

The Southeast accordingly promises to be a region of considerably greater importance as a resource producer and processor than it now is. Paradoxically, because of agricultural mechanization, it also is likely to be a continued source of low-income immigrants to cities of both North and South.

The possibility of some southerly extension of the northeastern-midwestern urban region must be considered a strong one. The growing importance of the Southeast as a resource base for the northern urban region, and its anticipated important increases in productivity, should make it increasingly important as a market. The attractiveness of manufactural location along the zone of contact between the northern region and the Southeast will be very definite. One part of this zone very clearly centers on the Ohio River, some sections of which already are industrialized. Signs of extension southward already are evident along the lower Tennessee. Should the Great Lakes-Ohio water connection eventually be realized, further extension of the urban region along the Ohio River line would be very probable.

Another probable extension of the present northern urban zone is southward from Washington in the direction of the already developed secondary industrial district along the Piedmont of the Carolinas (fig. 2, vol. 1).

THE COALESCING CENTERS OF THE NORTHERN REGION

The new expressways between the important existing urban centers may be expected to alter land use. Increases in the effective commuting distance, increases of range for the same shopping time and effort, and increased ease of highway freight movement will extend urban land uses farther into the countryside. Where existing centers are relatively close to each other, as along the northeastern seaboard, continuous urban land use between one center and another becomes even more likely. "Megalopolis" becomes more than a probability, particularly in view of the near 30-percent increase in population expected within the region in the next two decades. Similar effects may be expected, in a lesser degree, in the Cleveland-Pittsburgh, Detroit, Cincinnati-Dayton, and Chicago-Milwaukee areas.

The greatly increased coverage of urban land use, and the coalescence of previously individual urban centers which can be foreseen from the expressway pattern and population trends, raise, anew and more intensely, certain land-planning problems which have received some attention in the past. Among them are the access to and provision for outdoor recreation facilities.

THE PROBLEM OF OUTDOOR RECREATIONAL FACILITIES AND ACCESS THERETO

The coalescence or outward spread of urban areas in the northern zone can create some difficult problems of access to outdoor recreational facilities. As the urban spread continues more and more people will be placed farther and farther from facilities usable on a weekend, or a daily basis. Undesirable crowding of the public facilities available, already evident in the New York metropolitan area, may be expected to be general unless plans are laid to avoid it. This is certain not only because of the increased population density and lessening work hours but also because of further closing off of beach, lakeshore, or countryside for private use, as has happened along the accessible parts of the Atlantic coast line with surprising rapidity and completeness in the postwar period. The lack of ready access to such facilities already is visible in some areas; its intensification can be a handicap to the living of many millions in the future within this northern urban zone.

Measures to alleviate or meet the problem can be taken in two directions: (1) Planning and public action to reserve adequate open or "green" space in the path of the urban spread, which will be encouraged by the new highways. This means that foresighted and vigorous public action must accompany or precede private subdivision, commercial, and industrial growth. (2) Provision of more distant recreational opportunities, but still within easy reach of the urban development. Water facilities for outdoor recreation must certainly be included among these.

The latter suggestion illustrates in one way the ever closer relation which countryside and urban area are inevitably reaching. Yet a distinct separation of urban and rural planning still prevails. For instance, a national resource development activity of growing momentum is the rural small watersheds program sponsored by the U.S. Department of Agriculture. It already is operating in some areas significant in meeting urban present and future needs. Yet this is mainly a farm-oriented program, with little conscious attention to the possibilities and eventual need for coordinating rural and urban development. In similar manner relatively few of those who are preoccupied with the many perplexing problems of urban planning and development are conscious even of the existence of the small watershed program.

The gathering forces for urban spread in this northeastern-midwestern urban zone, and the new highways which will direct them, clearly call for leaving something of the countryside within the urban area, and for at least cooperative attention to land-use problems which a vast urbanization is bringing. These are problems in which foresighted private initiative can be important, but they also call for State and Federal Government alertness and attention.

Appendix 2

Water Resource Planning and Development in Agriculture [1]

To plan for water development, one first must make some assumptions about the agriculture of the future. What sort of agricultural industry, and what kind of demands, shall we plan for?

Although agriculture may not be what the stockbroker would call a "growth industry," it still has prospects for vigorous growth in the United States. It must grow, to meet the demands of a nation whose population may double before the year 2000. It must grow if the demands of an ever-improving standard of living are to be met. It must grow if U.S. commitments toward international leadership are to be honored from a strong position.

Economic projections of agricultural output as distant as the end of the century of course are subject to a wide margin of error. Even so, the population outlook alone leads to the conclusion that increase in agricultural output during the next decades is likely to be very large. This is the first assumption to be made about the kind of agriculture we reasonably might plan for: a much greater output than now, perhaps more than double that of the present day.

This larger production will be within a Nation different from the present one. Most citizens of this future Nation will live in cities and suburbs, and will be employed largely in nonagricultural industry. It would not be astonishing if the population directly supported by primary agricultural production fell to 5 percent of the country's total sometime within this century. Moreover, agriculture is likely to be even more closely integrated into the industrial system than it is now. Obviously the city of today could not exist without the products of the country. The dependence of the countryside on the city is less obvious, but equally true. The mechanized chemical-fed, research-based agriculture of today would only be a shadow of its present form without the efforts of the city. If we plan realistically, we shall plan for agriculture as part of a complex and highly interdependent industrial system.

The final assumption applies to the location of people and industry in the future United States. We now expect California to become the most populous State in the Union. Other sections of the West also will continue to grow, some rapidly. However, most of the people of the country will continue to live and work east of the Mississippi. Probably two-thirds of the great future growth which is expected will take place east of the Mississippi, and half of it from the latitude of Washington northward, within the East. I mention this because public planning no less than private planning should take account of the location of future markets. The continued location of the great markets for farm products in the East, and particularly in the Northeast and Midwest, is a factor of prime importance.

AGRICULTURAL USE OF WATER

How important is artificially supplied water to agricultural output? Conversely, how important is agriculture in water use? For agricultural use is only one of several important functions served by water in our economy.

The largest withdrawal of fresh water for any purpose in the United States is for irrigation. About 123 million acre-feet of water are estimated to have been applied to 34 million acres of farmland in the United States in 1955. This was about 44 percent of all the water withdrawn in that year. However, irrigated acreage was only about 9 percent of the total cropped land in the country for the same year. The value of products from irrigated farms was somewhat higher than the percentage indicated by the acreage. About 12 percent of the value of agricultural production in recent years is thought to have come from irrigated farms. It is therefore safe to say that agriculture is far more important in water development than artificially supplied water is in agricultural production.

This last assertion is borne out by the disappearance (consumptive use) of water in 1955. Approximately 74 million acre-feet of the water applied to irrigated fields is thought to have transpired from crops and pasture and evaporated during transportation or while standing on the fields. This amount probably was about 80 percent of all the water that disappeared in the course of withdrawal use.

How important should we expect irrigation water use to be in the future? It often has been said that water is the cheapest form of fertilizer. If this is true, one reasonably might expect additional irrigation to be among the means of adding to agricultural production in the remaining years of this century. Averaged over the past 25 years, irrigated acreage has increased about 1.6 percent per year. Should this trend continue for the remainder of this century, it would double the present irrigated acreage. But during the same period total agricultural production may be destined to increase much more.

BASIC REGIONAL PROBLEMS

The basic future agricultural water development problems can be seen clearly if we divide the country into three areas: The States east of the 98th meridian, the nine-State area of the Southwest, and the eight-State area of the Northwest. The position of each region in terms of knowledge of potentialities and needs for action will be summarized.

First, the East: This is where the major agricultural development of the future will be. This region has the lion's share of the land, the water, and the future market. As yet, however, irrigation has been practiced only on a modest scale. Aside from soil moisture received from precipitation, water is a minor agricultural input. Perhaps because of this we know very little about its productivity relative to inputs under the conditions prevailing in several parts of the East. Yet when we view such important potential agricultural areas as the lower Mississippi Valley the productive promise of water application appears to be of the first rank. An immediate need therefore is rigorous economic evaluation of the relative productivity of water in humid-land cultivation, in the light of modern agricultural technology. Wise and fruitful public investment for water development cannot be made without the findings from such studies.

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[1] Adapted with permission of the Journal of Soil and Water Conservation from an article of this title by the author in Journal of Soil and Water Conservation, vol. 14, No. 3 (May 1959), pp. 112-117.

Second, the eight States of the Northwest: These States, which comprise about one-fifth of the total surface of the country, have the land, and they have some water. Now sparsely populated, it is hard to foresee a population in this area during this century that will be more than about a 13th of the total for the Nation, or with a density more than one-fourth of the average for the entire eastern half of the country. This relation holds true even for a considerably more rapid rate of population growth in these States than for the country as a whole. Consequently, further opportunity for the development of irrigation agriculture may be expected there. Regional political pressure for such development also may be expected. Again the immediate need is one of obtaining further knowledge. There are three possible reasons for irrigation development in the Northwest: To supply the growing food demands of the eight States; to export to the Southwestern States; or to export to the East on the present pattern. To plan for water development we need to know the size of the market for products from irrigated lands, within the area itself. Even more, we need to know the likely productivity per dollar invested in this area to serve eastern and southwestern markets, compared with dollars invested on farms nearer those markets. We do not know these things at the present time.

Last, the southwestern region: We in the United States have not been accustomed to experience the pressure of population against resources. There have been local pressures on the land, but we always have had outlets for those pressures, and an ever-improving level of material living. The Southwestern States have had a bountiful share of the benefits from our economy. However, within the remainder of this century we shall see the first really serious pressure of population on a given resource in these States. (See app. 11.)

APPENDIX 3

BRIEF DESCRIPTION OF SYSTEMS ANALYSIS METHODS[1]

It should go without saying that all decision-making persons or groups attempt to economize, in the true sense of the word. That is, they try to make the most, as they conceive of the most, of whatever resources they have. Business firms may have a comparatively clear-cut notion of what they mean by the most, while consumers and governmental units have much more difficulty in defining it. But all of them, unless they make their decisions by drawing straws, are trying to do something in the best way possible with the resources that are available.

* * * * *

In tackling problems of choice, people have always found it advantageous to think about the consequences of alternative policies rather than to choose among them by, say, flipping coins alone. To assist them in predicting those consequences, they use models of the real situation. These may be small-scale representations, such as a model airplane in a wind tunnel or a pilot industrial plant. They may be representations on paper—mathematical models which grow out of laboratory experiment, reasoning, or the observation of small-scale physical models. Or, finally, these models may be simple sets of relationships that are sketched out in the mind and not formally put down on paper.

* * * * *

Some of the most fundamental analytical aids have long been available, and could have been used in the past to much greater advantage than they were. Although refinements have occurred, e.g., in the handling of uncertainty, the main elements of the theory of choice have existed for a long time, in economic theory, mathematics, and certain branches of philosophy, for example. This sort of aid indicates at least what questions should be asked in comparing alternative courses of action, and even without other tools, raising the right questions can generate simple models that are powerful problem solvers.

The spectacular advances over the past 50 years, however, have pertained to other tools. One thing that has happened has been the rapid development of all the sciences so that it has become possible to say much more about the relationship of one event to another—about the effects, for example, of using prestressed concrete or higher octane fuel, or about the relationship between smog and combinations of sunshine, ozone, and gasoline fumes. As missing links in the chains of relationship were filled in, it became possible to predict more accurately the consequences of various actions. This development has sometimes necessitated, in problems of sufficient importance, the collaboration of teams of scientists and analysts in order to bring the knowledge of specialists to bear.

Along with the better understanding of scientific relationships have come more and better data. Or perhaps the data might be described as one facet of that better understanding. In any event, more facts are available about plastics, rainfall, markets, disease, national income, and so on. Also, there have been refinements in the methods of statistical inference—for instance, in the use of small samples, sequential sampling, and experimental designs—and in techniques of computation and model building, such as linear programing. Finally, electronic computers have come along to make it practicable to utilize all the other refinements. More complex models, which in some cases yield more useful predictions, can be employed; more numerous calculations to show results in a wider range of situations have become feasible. In fact, some persons believe that modern computers mark a massive technological breakthrough, so far as analysis is concerned, somewhat as the microgroove recording was a crucial breakthrough in the high-fidelity reproduction of music.

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[1] Reprinted with permission from Roland N. McKean, "Efficiency in Government Through Systems Analysis," a Rand Corp. research study 1958, John Wiley & Sons, Inc., New York, pp. 3-8.

* * * * *

During World War II, modern statistical techniques and knowledge from different sciences were used, sometimes with striking effectiveness, in the comparison of military tactics, such as various deployments of aircraft or ships. As these studies were used to assist in operational decisions, they became known as operations research. Since the war, this general approach has been applied also to military development and procurement problems, which has meant peering further into the future, including a greatly expanded number of variables, examining a wider range of possible actions, and taking higher level alternatives into account. The comparison of such enlarged systems of interrelated elements has often been called systems analysis.

* * * * *

Despite the encouraging developments of analytical tools and of new applications, it is clear that the role of such analysis must be that of an aid to the decision maker, not that of a substitute for him. In the face of uncertainty about outcomes, for instance, operations research and kindred activities can assist, but not supplant, the exercise of judgment as to which policy is best. * * * Where the price mechanism and the action of competing firms do not attend to problems of choice—in internal decision of a consumer, government unit, or firm—it is operations analysis that often has no practicable rival.

APPENDIX 4

REPORT ON THE HARVARD PROGRAM OF RESEARCH IN WATER RESOURCES DEVELOPMENT[1] (EXCERPTS)

(By Arthur Maass and Maynard M. Hufschmidt)

PART I. IN SEARCH OF NEW METHODS: FORMAL CONDITIONS OF OPTIMUM DESIGN

Arthur Maass

What is wanted in new methods

The overall goal of the Harvard water resources program is to improve the methodology for the planning and the designing of multiunit, multipurpose water resource systems. * * *

We have three major objectives for the methodology.

The first objective is to allow the simultaneous consideration of a large number of alternative system designs. * * *

Second, our objective is to improve methodology for the planning of river systems so as to "marry" engineering and economics. * * *

Our third objective is to improve the methodology for design so that it can be adaptable to any reasonable economic objective and to any reasonable institutional constraints. * * *

The criterion of optimum design: The objective function

Much of the confusion, it seems to us, in applying economic analysis to the design of public water resource systems arises from a failure to draw a proper distinction between the basic objectives involved. * * *

One objective might be economic efficiency, defined very briefly and perhaps inadequately as a measure of the increase in real *national* income (note the word "national") resulting from national investment.

A second objective might relate to employment. * * *

A third objective might be income redistribution. This could be among regions * * * or income redistribution among classes or groups in society. * * *

Fourth, the objective might be economic growth. * * *

And, finally, there may be certain intangible objectives, just as legitimate as the tangible ones. * * * And of course there can be * * * any combination of these several types of objectives.

* * * If the objective * * * is efficiency, the design criterion—what we call the objective function—is as shown in part 1 of table A.

TABLE A.—*Objective functions*

Warning: No budget constraints

Static model

1. The efficiency criterion:

$$\text{Maximize} \sum_{j=1}^{n} \sum_{t=1}^{T} \frac{B_{vjt}-M_{jt}}{(1+i)^{t}} - \sum_{j=1}^{n} K_{j},$$

where

B_{vjt}=gross efficiency benefits of the jth unit in the tth year, where unit may also be project increment,
M_{jt}=operation and maintenance costs of the jth unit in the tth year,
K_j=capital cost of the jth unit,
i=discount rate,
n=number of units, and
T=life in years of longest lived unit.

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[1] Part of the proceedings of the Western Resources Conference, Boulder, Colo., July 13-17, 1959. (To be published by the University of Colorado, spring 1960.) The Harvard program is an outstanding experiment in the application of systems analysis to water resource development planning. Financial support has been given to it by the Rockefeller Foundation. Arthur Maass is professor of government, Harvard University, and director of the program. Maynard M. Hufschmidt is research associate in the graduate school of public administration, Harvard University, devoting his full time to the program. He was formerly a member of the program staff, Office of the Secretary, Department of the Interior. These excerpts reprinted with permission of the authors and the University of Colorado. Illustrations do not bear the same number designation as in the original copy.

2. Income redistribution, with an efficiency constraint:

$$\text{Maximize} \sum_{j=1}^{n} \sum_{t=1}^{T} \frac{(B_p+B_s)_{jt}-M_{jt}}{(1+i)^t} - \sum_{j=1}^{n} K_j,$$

$$\text{subject to} \sum_{j=1}^{n} \sum_{t=1}^{T} \frac{B_{pjt}-M_{jt}}{(1+i)^t} - \sum_{j=1}^{n} K_j \geq 0,$$

where

B_p=primary system benefits (efficiency), as above,
B_s=secondary system benefits (accruing to intended beneficiaries),

and other symbols are as in 1. above.

3. Efficiency, with an income redistribution constraint:

$$\text{Maximize} \sum_{j=1}^{n} \sum_{t=1}^{T} \frac{B_{pjt}-M_{jt}}{(1+i)^t} - \sum_{j=1}^{n} K_j,$$

$$\text{subject to} \sum_{j=1}^{n} \sum_{t=1}^{T} \frac{(B_p+B_s)_{jt}}{(1+i)^t} \geq B_r,$$

where B_r=a specified benefit level in the region and other symbols are as in 1. and 2. above.

* * * Part 2 of table A * * * is one example of how to combine an income distribution objective, with a certain degree of efficiency, into a design criterion.

An alternative is to specify in advance the distributive effects desired—for example, the desired income supplement in a particular region—as a constraint, and then maximize net benefits in economic efficiency terms, subject to this constraint. This, symbolically, is expressed in part 3 of table A. * * *

Finally on objective function, I should like to emphasize three points.

First, the several objectives, even where these are combined into a single complex objective function as in the last two equations, should never be so mixed or intermingled that their individual identities and relationships are obscured. * * *

Second, * * * the Harvard water program in its methodology is indifferent to the objective chosen. * * *

Third, though our method is indifferent to which objective, one must be chosen initially. * * * You cannot begin to plan or design a water system properly without a clear statement of the objective function as a design criterion.

* * * We will proceed now to set out more specifically the formal conditions for optimum design regardless of objective.

Maynard M. Hufschmidt

Formal conditions of optimum design

* * * Regardless of the objective specified, certain formal conditions must hold if the optimum system design is to be achieved. We define an optimum system design as that combination of system units and outputs for which net benefits are maximized, subject to whatever constraints are imposed. * * *

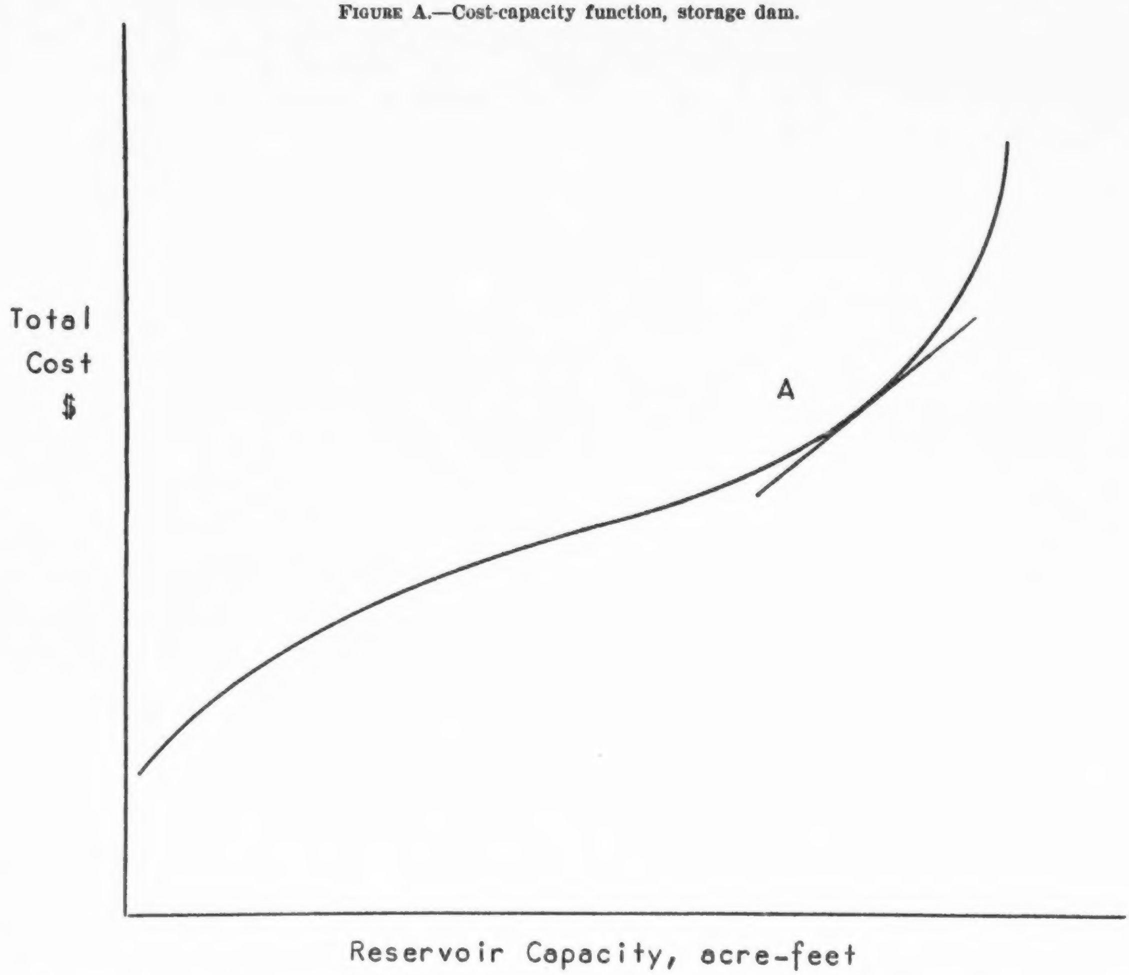
Now how can we tell analytically if we have attained the optimum design? We can test this by seeing if the specified formal conditions have been met.

These formal conditions are concerned with the behavior of three types of economic and technological relationships: first, the physical input-cost function; second, the physical input-physical output function, more commonly known as the production function; and, third, the physical output-benefit function.

As for the first, the input-cost function, we obviously want to design and construct such input items as dams, powerplants, canals, channels, pumping plants at least cost. * * * Using a dam and reservoir as an example, figure A shows the cost-capacity function for a storage dam. Over a range of feasible dam sizes, here is a schedule of least-cost designs for each capacity. Similarly, we could draw such functions for all other physical inputs to the system. The engineer does this intuitively under present practice when he selects two or three designs and finds then what the cost is, the cost calculation being done on the basis of standard design and construction practice, which to some extent assumes least cost * * *.

To illustrate the second type of relationship—the production function—let's assume a single physical output from the dam—say, domestic water supply drawn from the reservoir at a constant rate throughout the year. We have to make some assumptions as to the hydrology. But with these assumptions, we can draw an output-capacity curve, which shows for each reservoir capacity the maximum obtainable physical output—in our case, water supply. This is shown in figure B. The two curves shown in figures A and B are next combined to form a least-cost-output curve for the dam as shown in figure C. This curve shows the least cost for building a reservoir producing the specified output at the dam over the relevant range. * * *

Figure A.—Cost-capacity function, storage dam.



We turn now to the third type of relationship. On the assumption that gross benefits can be defined in terms of the objective function that is specified, whatever it is, economists can give us a gross benefit-output curve, as in figure D. We now transpose figure C—on a little larger scale—to figure D and we have the cost-output curve and the gross benefit-output curve on the same diagram.

Now we can begin to apply the formal conditions. By inspection of figure D we find the point of maximum net benefits—the point where the positive difference between gross benefits and costs in the greatest. At this point the slopes of the two functions are equal, or, in other words, marginal benefits equal marginal costs. This is the first formal condition for optimization in this example of a single dam for a single purpose. Stated more elaborately, this formal condition requires that we develop the system to the point where the derivative of the cost with respect to the output is equal to the derivative of the benefit with respect to the output * * *.

We now move to a somewhat more complex example, the two-reservoir, single-purpose case where we can still use the principle of equating margins * * *. We now obtain information on the total cost of developing two reservoirs in different-sized combinations, say reservoir A to 100,000 acre-feet capacity plus B at 300,000; A at 200,000 plus B at 200,000; A at 300,000 plus B at 100,000, etc.

From this information we sketch iso-cost contours or curves.

* * * These are curves which show the combinations of A and B which will provide the same total output, with output specified rigidly as, for example, municipal water supply with a particular draft requirement over time. In figure E there are indicated the points of tangency of sets of iso-cost and iso-output curves—the points where their slopes are equal. These points represent the least-cost means of providing the outputs involved * * *. In formal terms this equality of slopes means that the ratio of the marginal productivities of the reservoirs must be

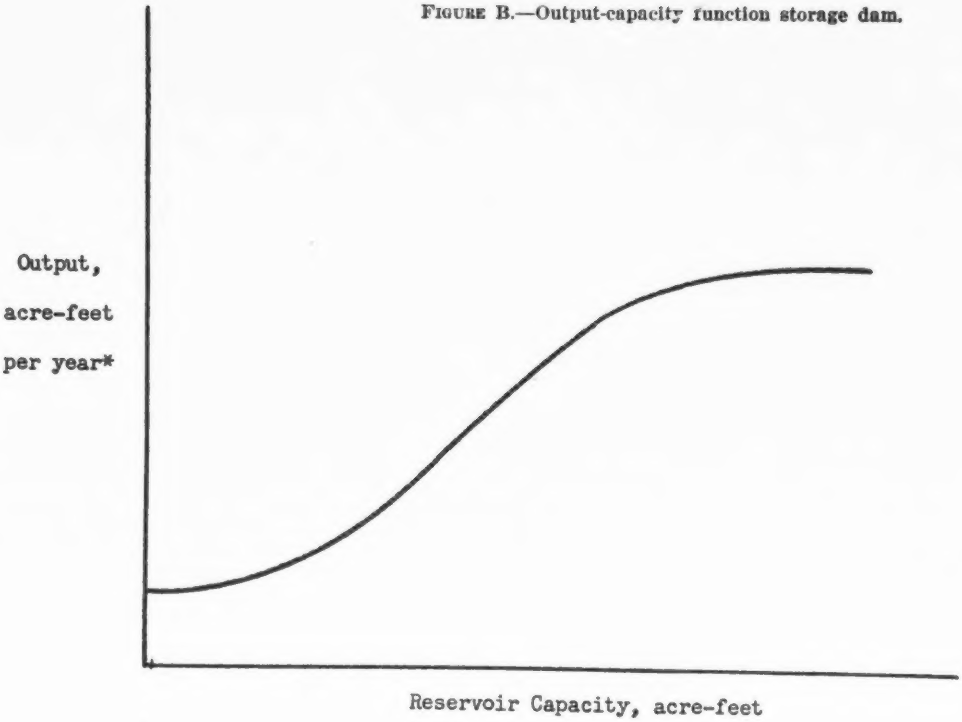


FIGURE B.—Output-capacity function storage dam.

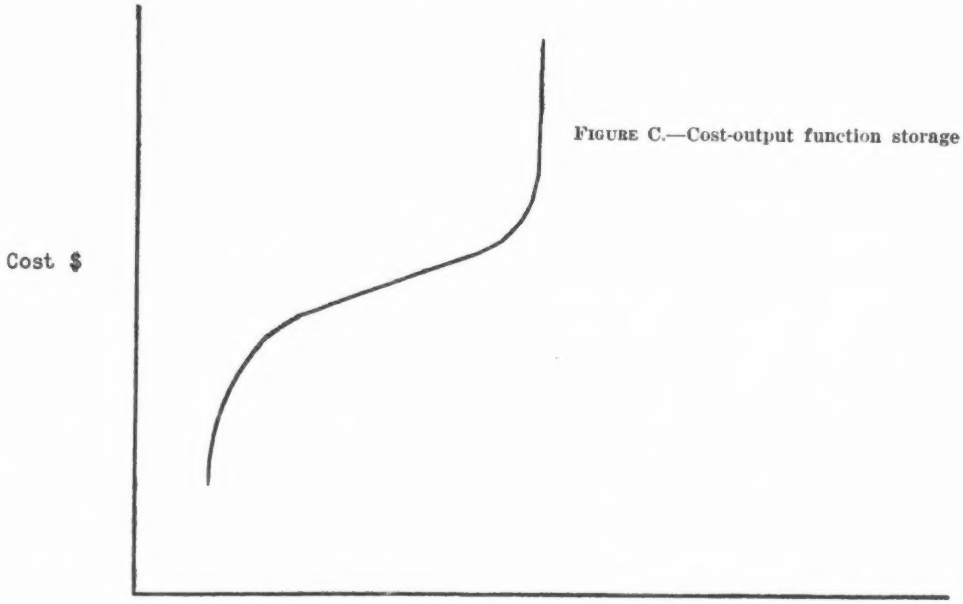
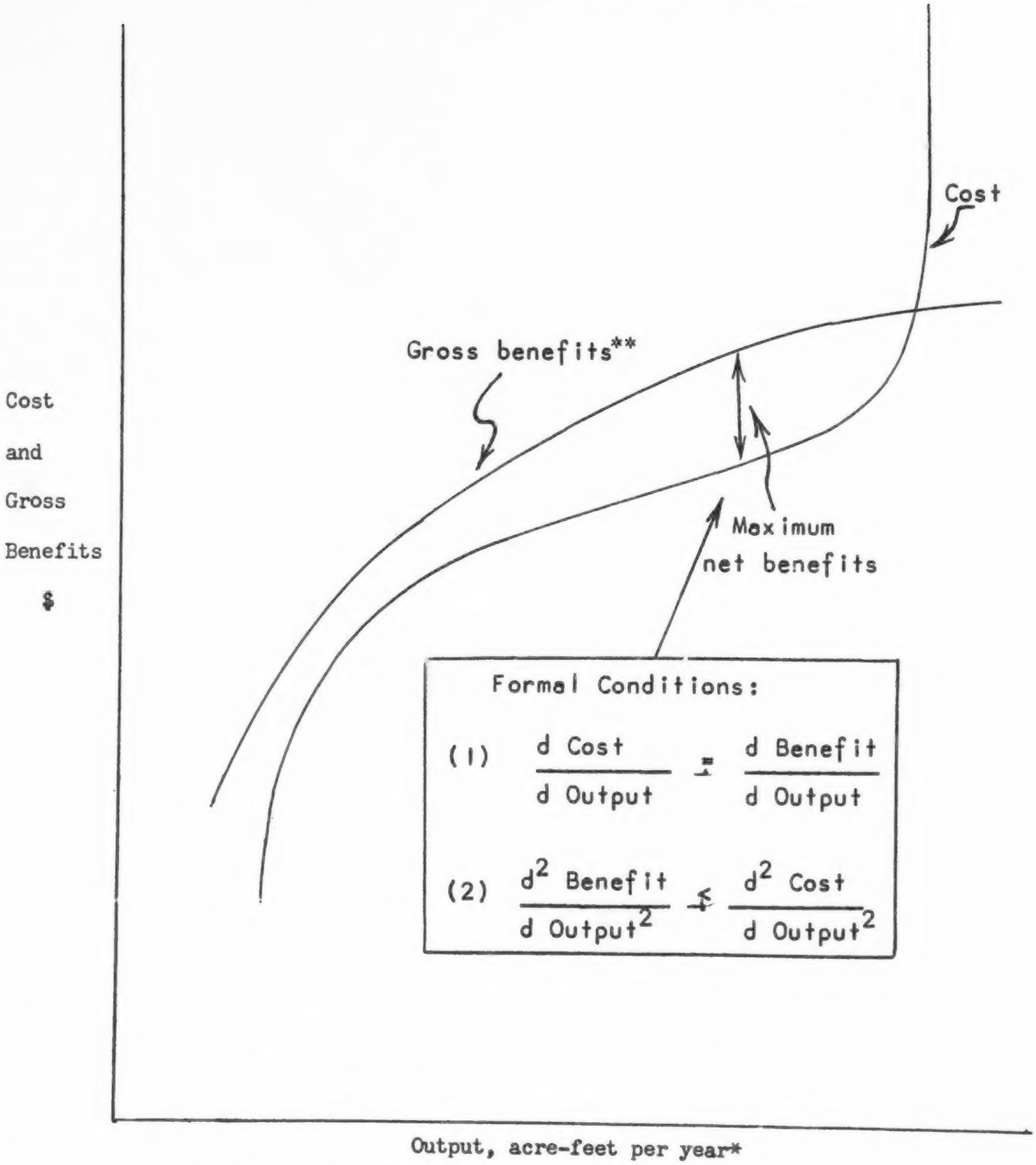


FIGURE C.—Cost-output function storage dam.

*With a specific time distribution throughout the year.

Figure D.—Cost-output and gross benefit-output functions.



* With a specific time distribution throughout the year.

** At the dam.

equal to the ratio of their marginal costs. Thus, if the marginal productivity of reservoir A is twice that of B, the marginal cost of A must be exactly twice that of B, neither more nor less. This is the first formal condition in this example.

You will note that the points of tangency in figure E are joined by a scale line which connects the least-cost combinations for producing these outputs. I can take this scale line and plot these points on the graph in figure D as the least-cost combination of the two reservoirs as a function of output. From here, the procedure is identical to the first case. Thus we have, for a two-reservoir, single-purpose case, two formal conditions: the ratio of marginal productivities of the reservoirs must equal the ratio of marginal costs, and, to obtain the proper scale of development, the marginal benefit must equal marginal cost.

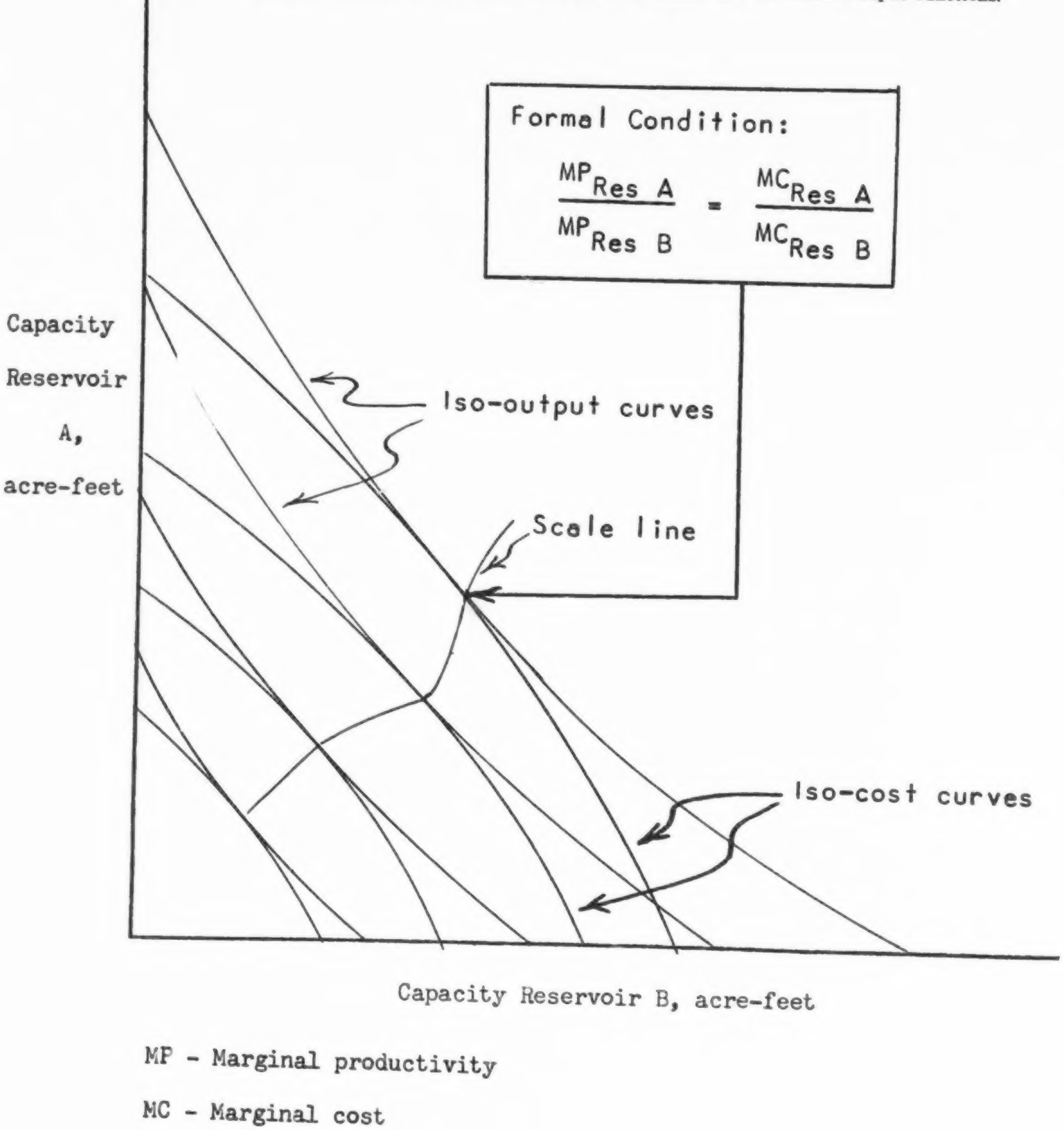


FIGURE E.—Two reservoir—single purpose system iso-cost andiso-output functions.

Formal Condition:
$\frac{MP_{Res\ A}}{MP_{Res\ B}} = \frac{MC_{Res\ A}}{MC_{Res\ B}}$
Capacity Reservoir A, acre-feet
Iso-output curves
Scale line
Iso-cost curves
Capacity Reservoir B, acre-feet
MP - Marginal productivity
MC - Marginal cost

I've sketched a simple case, and then a slightly more complex one, to indicate that the analysis can be extended, and formal conditions stated, for optimization of a complex multiunit, multipurpose system no matter how many units and how many purposes there are. Thus, for any single purpose, we can take the equation in figure E, transpose terms, and extend, as follows:

$$\frac{MP_{\text{Res A}}}{MC_{\text{Res A}}} = \frac{MP_{\text{Res B}}}{MC_{\text{Res B}}} = * * * = \frac{MP_{\text{Res n}}}{MC_{\text{Res n}}}.$$

We can write a similar expression for every other purpose, and obtain a matrix. The number of columns corresponds to the number of reservoirs, and the number of rows to the number of purposes.

The second formal condition for the general case relates to the optimum levels of outputs. If we assume no budgetary constraints, the marginal gross benefit of producing each output must equal the marginal cost of producing it. If we have budgetary constraints we can't develop the system to the point where the marginal benefits equal the marginal cost of producing each output. In this case, the marginal cost of producing the last increment of benefit must be equal for all purposes.

I have outlined these formal conditions in an oversimplified way and have assumed smooth curves and surfaces. This helps us to visualize the problem that we'll be dealing with * * * (in which) we shall actually use some of these formal conditions in our methodology. They all must be satisfied by the optimum combination, but in some cases we can use the formal conditions directly, and they always provide us with clues as to the best methodology. Also, looking at the formal conditions focuses attention on * * * the point of juncture between the engineer and the economist—the production function. I define this as the function which relates physical inputs to physical outputs and which shows the maximum quantity of one physical output which is obtainable for each possible combination of the remaining physical outputs and the physical inputs. * * * Much of the research in our program is concerned with determination of the production function for complex river systems.

Finally, a few words on uncertainty as it affects the formal conditions. Curves (A–E) have been drawn as if costs, outputs, and benefits were single-valued functions. Yet, as we know, they are all subject to uncertainty because of physical factors such as hydrology and economic factors such as changes in supply and demand for goods and services over time. In fact, we do not have single functions—we have ranges within which values are most likely to vary. Thus, for example, figure F shows an expected net benefit-scale of development function with confidence limits. It is obvious, of course, that as the scale of development increases, our confidence limits broaden because of hydrologic or economic uncertainty. * * * We may not wish to settle for the combination yielding maximum expected net benefits if associated with it is too wide a range of uncertainty—if the confidence limits are too wide. We may be willing to settle for lower net benefits but have them more certain. This, of course, we can do in a number of ways. One is to build a greater degree of flexibility into the design of the system at an increased cost. We must recognize that uncertainty pervades the optimization problem, and the objective functions and formal conditions should be adjusted to take proper account of it. * * *

(In Parts II and III of their report, Maass and Hufschmidt describe two approaches which they and their colleagues have examined in their search for feasible methods of attaining optimum design. One is the simulation of river flow on a high-speed digital computer, using the machine to evaluate many alternatives and to produce a design compatible with programed objectives and constraints. Another is the use of simplified mathematical models which apply the techniques of queuing theory and linear and quasi-linear programing.

(The simulation approach has been tested by them on a prototype river basin of their own devising, whose hydrology is based on that of the Clearwater River, Idaho. Seven physical structures were included in the prototype, including four reservoirs (A, B, C, D), two electric power generating plants (B, G), and a diversion dam (E). (See fig. G on the following page.) Maass describes their initial steps in the following excerpts.)

* * * I shall indicate very briefly our overall strategy—what data we give to the machine and what results we seek to get from it.

The data we give the machine are of two classes.

In the first place there are a number of variables—that is, units and outputs—for which we can vary the size or the magnitude for any simulation run by the machine. One series of variables is the system units, set forth in table (B).

TABLE B.—*System units and outputs*

Units:	*Range of scale*
Reservoir A	0 to 1,500,000 acre-feet.
Reservoir B	0 to 15,000,000 acre-feet.
Reservoir C	Do.
Reservoir D	0 to 13,000,000 acre-feet.
Dead storage, reservoir B.	0 to 15,000,000 acre-feet.[1]
Powerplant B	0 to 800,000 kilowatts installed capacity.
Powerplant G	Do.
Outputs:	*Range*
Irrigation	0 to 6,000,000 acre-feet per year.
Power	0 to 4,000,000,000 kilowatt-hours per year.
Flood control	Maximum stage to stage corresponding to 105,000 cubic feet per second flow at control point G.

[1] Subject to the following constraints:
Maximum powerhead $\leq$ twice the minimum powerhead.
When powerplant $B=0$, dead storage $=0$.

FIGURE F.—Net benefit-scale of development function.

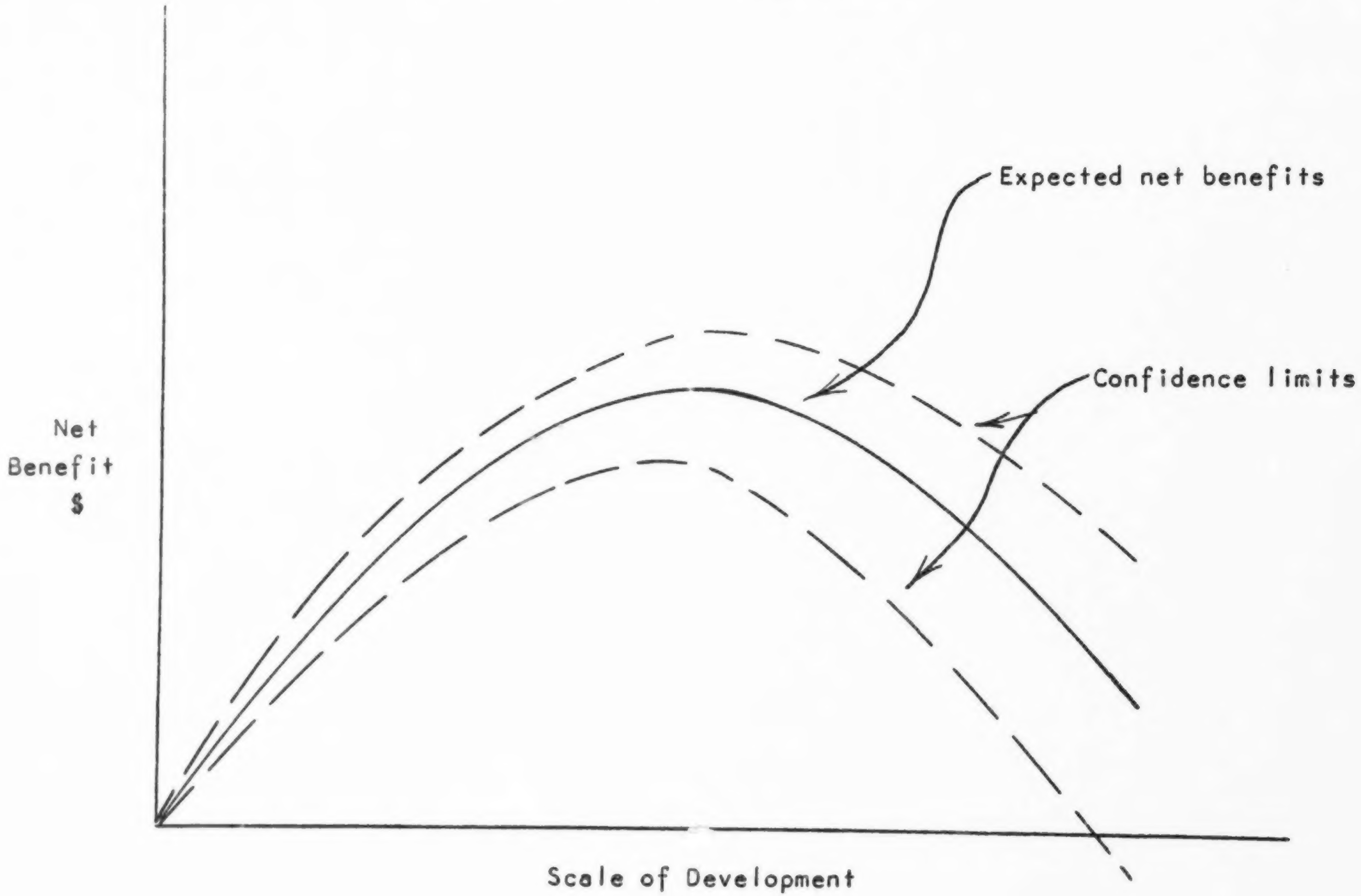
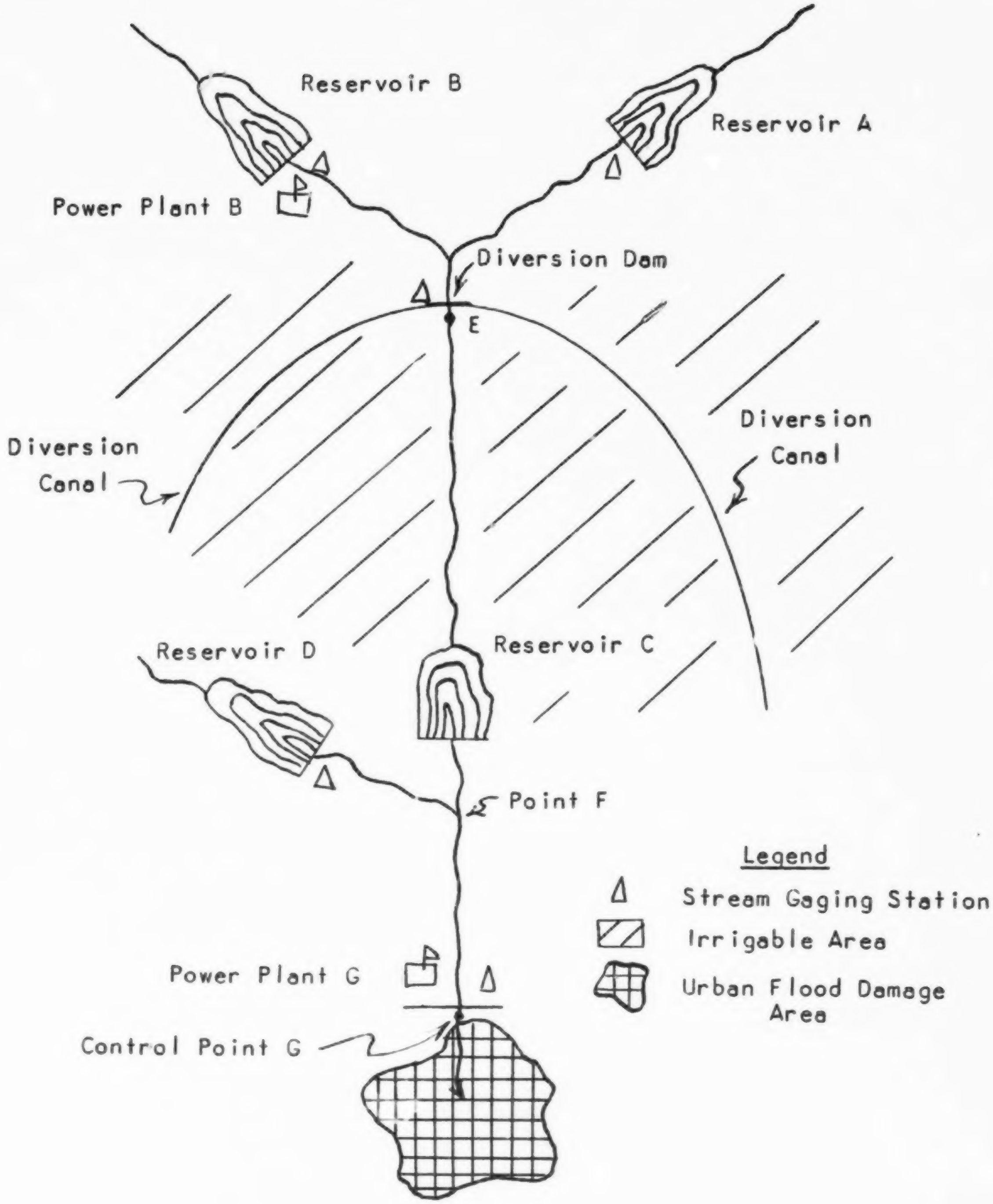


FIGURE G.—Prototype river basin system.


Reservoir B
Reservoir A
Power Plant B
Diversion Dam
E
Diversion Canal
Diversion Canal
Reservoir D
Reservoir C
Point F
Legend
Stream Gaging Station
Irrigable Area
Urban Flood Damage Area
Power Plant G
Control Point G

For each simulation run of the machine we provide a value for each of the seven system units and a value of output that we should like to get for each of the three system purposes; and we see how much we get in the way of benefits and what the costs are for that particular combination of variables. Then, if that combination does not look profitable, we try another, and another, by the hundreds. * * *

There are two other types of variables I should mention, closely associated with the system units and the system outputs. At each level of each system unit there are costs—capital costs and operating and maintenance costs. * * *

In addition to the variable data, there are two constants. First, the hydrology. We have the hydrologic record for this river, roughly 32 years of monthly observations at five stream-gaging stations. That doesn't change. * * * The second constant is the operating procedure—the instructions we give to the machine on how and when to store and release water. * * * Thus, for any one machine run you select any combination of variables, and the machine operates the entire system in accordance with the operating procedure you have given it, using the flows of the given hydrology. * * *

When the run is over, the machine gives a benefit evaluation in dollars. * * *

The only really difficult problem in machine simulation is how to give the machine its instructions on operating procedure—in our case, when and where to store and when and where to release. In recent years, happily, advances in the use of computers for simulation-type operations have been tremendous, and one of the most significant of these is a new machine language known as FORTRAN II. We wish now to tell you something about our problems in instructing the machine. * * *

Maynard M. Hufschmidt

Instructing the machine

Simulation of a river system on a high-speed digital computer requires a combination of skills and talents, chiefly of the engineer hydrologist, the mathematician, and the machine programer. We meet, therefore, the problems of communication between experts in different disciplines. As long as the river engineer did simulations by hand in his own separate operating studies he was in complete command of the entire strategy. He could adjust his rules of procedure as he saw fit. He did not need to formalize them unduly. But simulation on the computer requires him to spell out his rules in considerable detail, so the machine programer can translate them into machine language. * * *

I propose to sketch briefly one procedure for putting the rules into machine language, for the IBM 704 computer. * * * I shall for illustration use a simplified version of the prototype system just discussed * * * (fig. G). I am going to use only some of its upper part, reservoirs A and B only, without powerplant B, and I shall deal with the irrigation function only.

To simulate this two-reservoir single-purpose system on the machine the first step of the engineer is to formulate his basic policy of operating procedure and state it in very general terms as follows:

Step A: Basic policy of operating procedure.—Release no water from either reservoir unless necessary to meet specified monthly irrigation diversions. Apportion the required releases between the reservoirs so as to equalize their respective probabilities of being refilled and thus minimize unnecessary spills (i.e., spills from one reservoir when there is available space in the other). Do this by attempting to apportion releases so that the total of the expected available space in the two reservoirs at the end of the month will be divided between them in the same proportions as their expected mean inflows, respectively, over the remainder of the drawdown-refill cycle.

The second step is to elaborate this basic policy of operating procedure by setting it forth as a sequence of rules or steps stated in an informal textual (as opposed to mathematical) fashion:

Step B: Informal description of month-by-month operating procedure.—

1. Compute the spill from reservoir A, and set the release from A to zero.
2. Compute the spill from reservoir B, and set the release from B to zero.
3. Compute total flow at E available for irrigation diversion without releases at A or B.
4. Compute excess of total available flow at E (as computed in step 3) over irrigation diversion requirement.
5. Compute the portion of the irrigation diversion requirement to be met from releases from A and B.
6. Compute irrigation shortage (if any) after all available water in A and B has been used.
7. If the quantity computed in step 5 is negative or zero, no releases are required—proceed to step 14; if positive, proceed to step 8.
8. If irrigation shortage (as computed in step 6) is positive or zero, empty both reservoirs and proceed to step 14; if negative, proceed to step 9.
9. Compute the total reservoir space available in A and B after required releases are made.
10. From given data of inflows to A and B for the remaining months of the reservoir drawdown-refill cycle, compute the proportions of the total inflows for this period which occur at A and at B.
11. Apportion total reservoir space (as computed in step 9) between A and B in accordance with the proportions computed in step 10, subject to physical constraints.
12. If the apportioned reservoir space as computed in step 11 is greater than total reservoir capacity for either A or B, use the lower figure as the space allocation, and assign the remaining space to the other reservoir.
13. Compute the release from each reservoir by subtracting space available at each reservoir before release from space as computed in step 12. Neither release as so computed can be negative.
14. Compute reservoir contents of A and B at end of month, and return to step 1 for next month.

These 14 rules, which spell out the general policy, are still not specific enough for a programer to handle as instructions to the machine. They deal mostly with preliminaries and not sufficiently with the actual process of apportionment. Thus items 1 to 4 are the rules for taking advantage of any free water we have—water available before we have to release. Items 5 to 8 are the check of boundary conditions: if we don't have to release any water at all, or if we have to release all the water, there is no occasion for apportionment. Only items 9 to 13 are the rules for apportionment.

The third step is to restate this sequence of rules in formal mathematical terms, using also a simple flow diagram to help us visualize branching where we have to make choices. Standard algebraic terminology is used at this point quite generally. But we are using some terminology of the FORTRAN II method of programing. In FORTRAN II language our rules are stated at this point with the help of equations, and the equations use symbols which we make up ourselves. Provided we observe certain conventions imposed by the machine, we can make up any symbols that make sense to us. What we have tried to do is make up symbols which, while being understood by the machine, can at the same time be very easily read as plain English. * * *

Up to this point the task is the engineer's: to describe the problem in a manner readily intelligible, without the jargon of programing. Beyond this point * * * it has been necessary until quite recently for the programer to take over. But the recent development of a new coding system, FORTRAN II, has radically changed the situation. This new language greatly reduces the further work involved in converting the problem description into a form acceptable to the computer, and it permits the new knowledge necessary to effect that conversion to be acquired by a skilled engineer or technician in a very short time, although the services of skilled programers, or engineers trained as programers, are still required. * * *

The machine will now take this language and do the detailed programing inside. This was formerly a rather arduous task of the programer and furnished a tremendous number of opportunities for plain human error. * * *

Thus, thanks to FORTRAN II and to other advances in computer technique, the unique advantages of the large computers, with their tremendous storage capacity, are now becoming more and more available to river system simulation.

But we do not want to give you the impression that simulation by machine involves no serious problems. In fact, it is subject to certain inherent limitations, to which, however, there are some partial answers. * * *

Arthur Maass

Limitations of simulation

The first limitation is the tremendous number of possible combinations of the different variables. The number depends on what increments you take in the size of the several units * * *.

A second limitation, and I think a more severe one, follows from the fact that the operating policy must be given to the machine * * *.

A third limitation * * * is this. The operating policy is chosen by the engineer or the planner according to his experience * * *. The operation policy may be in error, and our simulation may not have married engineering and economics sufficiently.

The fourth and last limitation relates to the actual stream hydrology. This hydrology may in fact be a very limited representation of the possible configurations of flows of the stream. * * *.

Maynard M. Hufschmidt

Partial answers to the limitations

The first limitation is the enormous number of possible combinations—far more than we can possibly test, even with a high-speed machine. * * * Sampling is our first partial answer.

There are two broad classes of sampling techniques—random sampling and systematic sampling.

With random sampling we would, as the name implies, select completely at random the level of each of our variables—the inputs and the outputs. * * * The random sampling technique as a means of approaching the optimum benefits may turn out to be very valuable indeed.

But it has other important advantages as well for water resources systems. In the first place, it is often particularly advantageous when the number of variables is large, as is likely to be true in actual water resources systems. And in the second place it is not adversely affected by a high degree of interrelationship among the variables—again a common situation in water systems, where, for example, the size of one reservoir will have an effect upon the required size of another, or an increase in irrigation output will increase the electric power realized as a byproduct. So random sampling appears to be a good method to use as a first stage in analyzing a complex system. * * *

As for systematic sampling, the second broad class of sampling techniques, its essence is to apply some order or strategy to the selection of the combinations to be analyzed. I shall discuss three methods of systematic sampling—the uniform grid method, the steepest ascent method, and the single factor method.

The uniform grid method is a systematic way of examining the entire range of combinations. * * * The advantage of this method is, of course, that it provides a uniform coverage. Also, it is not greatly affected by the degree of interrelationship among the variables. * * *

The second method of systematic sampling is the steepest ascent method. In contrast to the random method and the uniform grid method, which both try to cover the whole surface or a substantial portion of it in an operation mapped in all detail at the beginning, the steepest ascent method is a step-by-step, sequential procedure, with later steps determined by the results of earlier ones. * * *

The third method is the single factor method. This method, too, is a sequential or step-by-step method but it differs from the steepest ascent method in that it analyzes each variable one at a time. It finds the optimum combination obtained by varying one variable and then uses this combination as a starting point for analyzing a second, and so on. * * *

Now each of these methods—random sampling and the three types of systematic sampling—has its particular advantages and disadvantages. The methods, thus, are suited to be used in combination. For example, where little is known of the nature of the net benefit surface being investigated, particularly if the number of variables is large, we might start out with random sampling as the first method for examining the entire surface. If one or more regions of interest are thus identified, these can be analyzed further by another random sample, or by a uniform grid sample. * * * From what we know of the net benefit surfaces of water resource systems * * * it appears that in most cases all the methods described above can be used to some degree. Our hope is that through use of such methods the number of combinations we investigate can be kept at a reasonable figure. Yet the number may still be large, even for a high-speed computer. This fact remains a limitation of the simulation method. * * *

Another limitation * * * relates to the operating procedure itself. Owing partly to the difficulties in formulating operating procedures * * * and owing partly to the difficulties in programing operating procedures, we don't know as much about them as we should like to. * * * We don't know at this time the sensitivity of the output of different water resource systems to different operating procedures and the significance of large and small variations in procedures. * * * In effect, the operating procedure * * * becomes another variable in the analysis of our system, a variable concerning which we know very little at the outset.

There are three methods of handling the operating procedure problem that we have been investigating.

The first is to formulate a relatively small number of separate operating procedures, each with its distinctive logic, and each to be programed for the machine. This is the method with which we started and are currently working. * * *

The second method we have thought possible * * * is to develop a very generalized master operating procedure within which the detailed logical rules can be varied within certain limits. * * * We would program a master operating procedure in a manner permitting a number of detailed subprocedures to be developed as needed and brought in or taken out by switches, without reprograming. * * *

The third method is to develop what hopefully one would call an optimum operating procedure as an integral part of the machine program. The rules formulated initially would be very general, and they would assume some knowledge of future flows or some degree of forecastability, or at the very minimum they would use the statistical characteristics of the inflow to modify the procedure by time increments, usually by months. We would be able to change the detailed rules automatically in the machine, instead of having them fixed. In this way the detailed operating procedure itself would change month by month as the machine searched for a theoretically perfect set of rules for each combination of inputs and outputs. * * *

Now just a few words on the question of hydrology. The simulation procedure is based on the particular hydrology given to the machine—in our case, as we have said, the actual hydrology of the Clearwater River. Therefore, the results we get are strictly valid for that particular configuration only. * * * Now the weakness inherent in this limitation has long been recognized in the case of flood events, where the extreme events are crucial to the analysis. There has been use, therefore, of frequency analysis in handling the extreme events. But for machine simulation, particularly where the existing record is shorter than 50 years—and that is generally the case—the only answer is to turn to a synthetic record which will bring in other configurations of the data—other maximums and minimums and different spacings of these. By serially correlating the mean monthly flows and by applying appropriately sized random components to the systematic base furnished by the correlations, it is possible to develop synthetic monthly flows which can be spun out by the machine with a relatively simple program for as long a period as you wish—for 500 or a thousand years. * * * This technique, admittedly, is not beyond the experimental stage and thus must also be classified as only a partial answer.

Arthur Maass

* * * These are only partial answers to the problems raised. * * * We should like to be able to proceed more directly to the very heart of the multipurpose, multiunit problem. We should like to be able to derive a solution which gives at once optimum sizes of units, optimum outputs, and optimum operating procedure. This we have tried to do by skeletonizing and simplifying the system and by trying to use a simplified mathematical model. * * *

(The second method for evaluating a large number of alternatives simultaneously tried in the Harvard program is the use of mathematical models. In the model studies made thus far the Harvard group has used prototypes which are simpler than that employed for the simulation technique. One of these prototypes (fig. H) is composed of a stream with a total wet half-year flow of 6.9 million acre-feet and dry half-year flow of 3.9 million acre-feet. Two reservoirs (A and B), an irrigation diversion (I), and a single powerplant (C) compose the super-imposed development. The problem set for this prototype was one of determining the capacities of the reservoirs, the irrigation diversion, and the energy output so as to maximize possible net benefits from the system. An expression was developed for the objective function (achieving maximum net benefit), recognizing certain economic and technical constraints (like powerload factor), and recognizing also some subsidiary functions of scale. This expression becomes

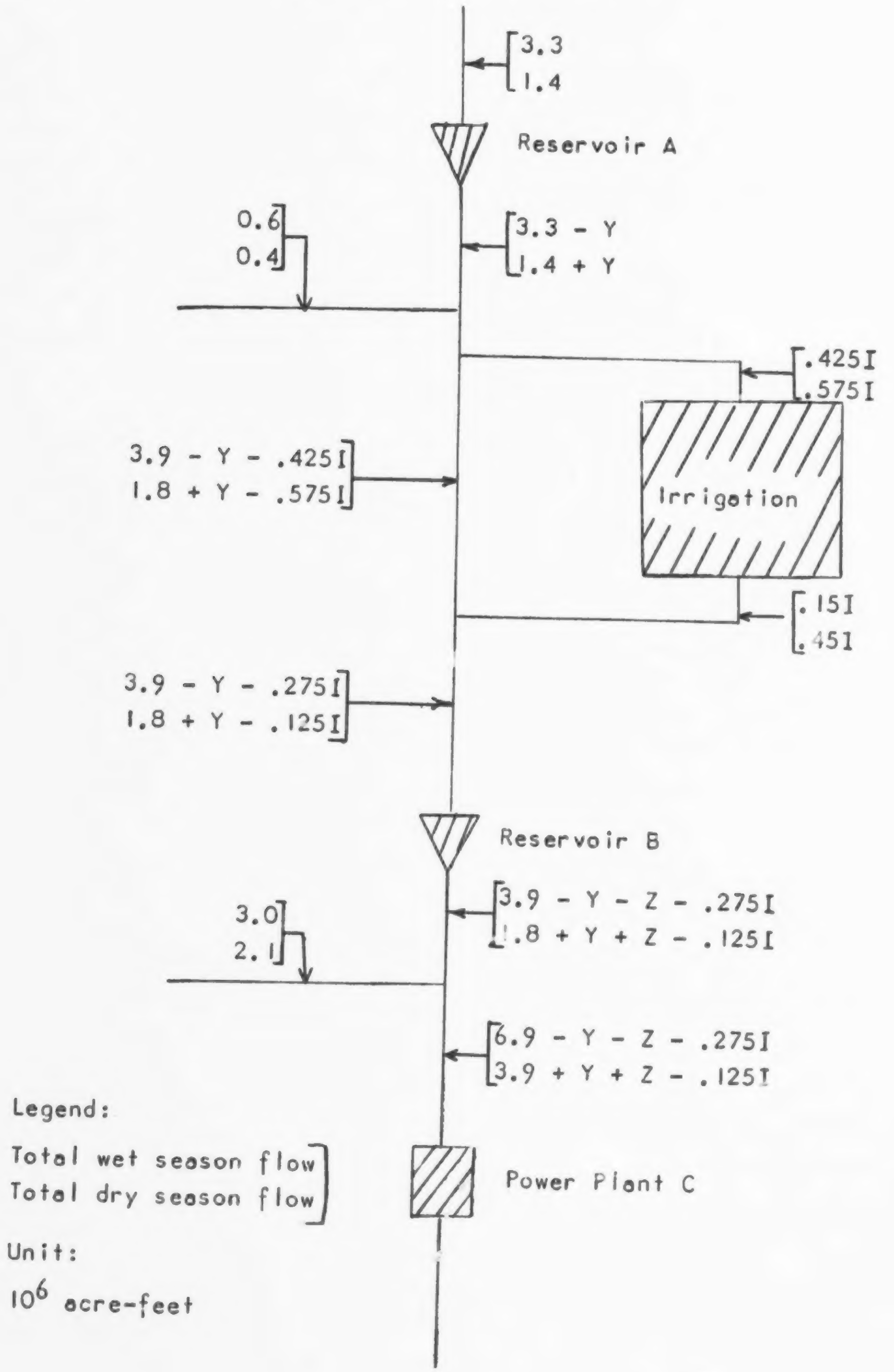
$$\begin{gathered} II = 229.4E + E^2 + 1.4I + 1045 \log(1 + .2I) \\ -50.1\,(I-3) - 4.5I - 0.5(I-3) \\ -\frac{43Y}{1+.2Y} - \frac{47Z}{1+.3Z}, \end{gathered}$$

where

E = energy in billion kilowatt-hours,
I = irrigation water in million acre-feet,
Y = live storage capacity of reservoir A, in million acre-feet,
Z = live storage capacity of reservoir B, in million acre-feet.

The solution to this equation is described by Maass.

FIGURE H.—Map of Simple Valley.


3.3
1.4
Reservoir A
0.6
0.4
3.3 - Y
1.4 + Y
.425I
.575I
3.9 - Y - .425I
1.8 + Y - .575I
Irrigation
.15I
.45I
3.9 - Y - .275I
1.8 + Y - .125I
Reservoir B
3.0
2.1
3.9 - Y - Z - .275I
1.8 + Y + Z - .125I
6.9 - Y - Z - .275I
3.9 + Y + Z - .125I
Legend:
Total wet season flow
Total dry season flow
Power Plant C
Unit:
10^6 acre-feet

Finding the unknowns

When you have, as here, a complex objective function, accompanied, as is this one, by constraints that are linear or near-linear, the problem is susceptible to solution by what we call quasi-linear programing. * * *

First, you select certain variables, give each of these a particular value, and freeze them at those values. Then you try to maximize the objective function by changing the other variables. When you have succeeded in that, you test to see whether it would be advantageous to unfreeze or change the assumed values of the "fixed" variables. If so, you freeze these again at new test values and maximize over again. And you keep trying as long as you get better answers. * * *

In this particular case, without going through the details of the derivation, we find that the maximum value you can get from the system is $490 million and that associated with this value are a capacity in reservoir A of 1,275,000 acre-feet, a capacity in reservoir B of zero acre-feet, an irrigation output of 3 million acre-feet, and an energy output of 1.4 billion kilowatt-hours. The irrigation output, you will note, is optimal at the point beyond which you have to bring in the pumping. It doesn't pay to bring in the pumping with the additional capital and operating and maintenance costs involved.

Now, I ask you to note what we have achieved. We have determined, all in one problem and in one solution, the optimum objective with the optimum outputs, the optimum sizes of system units, and the optimum operating procedure, and we have effected, I believe, a good marriage between engineering and economics. What is the operating procedure? Well, it is the specification of values for the internal flows. If you take these internal flows and then put in the values we have derived from Y and Z and E and I, you have the operating procedure. So by this mathematical model we have, in a sense, achieved the objectives sought, though I should add that this was not done on first try. * * *

(Certain limitations of the technique are then described. One is complexity; solutions "by hand" cannot treat a system much more complex than the prototype. However, machine computing is much less limited in this respect, and probably can be adapted to the complexities encountered in actual river system planning. The second limitation is incapacity to handle factors not fully predictable, like unusual hydrologic events. Here the application of queuing theory is considered an answer. Hufschmidt describes its application to the model.)

* * * By a new application of queuing theory it is possible to calculate a factor which can be added into the deterministic model to take account of the unpredictable year-to-year fluctuations in flow. I shall not attempt to describe queuing theory, but its name is derived from the notion of the queue, the waiting line at the box office, for example. In a river system the water in a reservoir is the queue. The inflows into the reservoir are the additions to the queue. The releases from the reservoir are the ticketholders moving through the turnstiles.

Our combined model, in which this factor is added, deals with hydrology as follows: First, you find from the hydrologic record the annual mean flow and the mean flow for the seasons or months with which you're going to work. Second, you identify the year-to-year fluctuations around these means—identify them in terms of statistical measurements. The model calculates the reservoir storage needed to convert these seasonal means into useful output. This it does by computing the annual fluctuations in reservoir content, occasioned by the mean flows and the specified seasonal withdrawals. This is, in effect, the deterministic component. For the stochastic component the model calculates the additional storage needed to deal with unpredictable year-to-year fluctuations around these means. This it does rather simply by taking account of the standard deviations of the seasonal inflows. I don't pretend to understand why this is so, but apparently taking account of standard deviations, which are very simple to calculate, is almost enough by itself, without resort to more complex statistical measures, to allow for the stochastic element. Thus we can get the optimum design for the Simple Valley project with provision for overyear storage and stochastic variations in hydrology. And if we learn to solve more complex systems, such as the prototype, by quasi-linear programing on a deterministic basis, we can also solve them on a stochastic basis. * * *

(The advantages and limitations of both approaches are then discussed, and a conclusion reached that a combination of the two methods may yield a more efficient approach than either one alone. Maass summarizes as follows.)

The total strategy

Now, to recapitulate. We have simulated the riverflow, with structures and outputs, on the digital computer. In this, we have done little more, conceptually, than follow existing planning procedures, but instead of doing hand studies of just a few alternatives we can, by machine, examine hundreds. But we were not satisfied, even with powerful techniques like random sampling, to select the combinations of variables to be examined, that we would reach our objective efficiently. We have therefore sought to skeletonize or to simplify the problems to see if we can thereby, using mathematical models, approach in one and the same operation optimum sizes of structures, optimum operating procedure, optimum outputs, and, of course, optimum net benefits. Now assuming the mathematical models work, they are an adequate strategy for design of simple systems. But for more complex systems, perhaps even for the prototype * * * the mathematical models are likely to give an approximation only, or what we should call a good first fit. And with this good first fit we should then proceed to the machine and set up the simulation to improve on the first approximation. * * * The operating procedure which we program—the instructions we give to the machine on how it is to operate the system, when to store and release—will be optimal or near-optimal because we will have worked it out in the mathematical model. And the combinations of variables which we select for machine studies will be similarly in the region of the optimum because that region will have been indicated by the mathematical model. * * *

APPENDIX 5

SYNTHETIC HYDROLOGY AND PROBABILITY ANALYSIS

Past water development planning has relied mainly on history of flow as recorded by stream gages for its engineering hydrology. The planner finds that such records are less than adequate for projecting the course of hydrologic events in the future for three reasons: (1) The record may be too short to provide a reliable sample. As Leopold has noted, "A streamflow record represents a time sample out of an indefinitely longtime period."[1] Many North American stream records do not present a long series. Fifty years' data comprise a long record here, and many stream reaches have shorter series. (2) There is no assurance that during any succeeding period of the same number of years as the record total runoff will be the same as that of the record. (3) There is no assurance that the sequence of hydrologic events within the historical period will be the same during any future period as that of the period of record.

Attempts are being made to lessen the handicaps of the planner in these respects by the application of statistical analysis and the construction of synthetic data series.

Probability analysis has been applied to the first two of the handicaps attached to the use of historical records. This analysis is the application of statistical techniques so as to give quantitative indications of the likelihood that given events will occur at a particular time, or within a stated period, in the future. By these means Leopold has shown that the flow means of periods as long as 200 years may still have a significant variability, although the variability of so long a period is less than that of periods of shorter duration. He has also shown, as he explains: "* * * the tendency toward persistence in meteorologic and climatic events leads to a larger variability of mean values than if the same events occurred in random order."[2] Thus total flow over given periods has a probability of varying within measurable limits, those limits corresponding to the length of the period analyzed. Accordingly, by the use of statistical techniques it is possible to obtain from any flow record of reasonable length some quantitative indication of the likelihood of future patterns of runoff in a stream.

Synthetic hydrology applies statistical techniques to the generation of data which may be used with greater confidence than simple historical series in projecting the sequence of future flows. An experiment with such hydrology has been part of the Harvard program described in appendix 4 above. Maass and Hufschmidt describe their method as "serially correlating the mean monthly flows, and applying appropriately sized random components to the new systematic base provided by the correlations. In this way synthetic monthly flows can be generated for as long a period as desired; and as many as 500 to 1,000 years can be run relatively quickly on computing machines.* * *

"The synthetic data, which would then be used as input in any method of analysis, should give superior information for design purposes on the range of the number and severity of shortages and floods which may occur over the economic life of the system and on the range of expected benefits to be produced by the system in its economic life or any part thereof."[3]

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[1] L. B. Leopold, "Probability Analysis Applied to a Water Supply Problem," Geological Survey Circular 410, p. 2.

[2] Leopold, op. cit., p. 11.

[3] A. Maass and M. M. Hufschmidt, "In Search of New Methods for River System Planning," Journal of the Boston Society of Civil Engineers, XLVI (2), Apr. 1959: 116.

APPENDIX 6

REASONS FOR AN ECONOMIC ANALYSIS OF WEATHER MODIFICATION[1]

An economic analysis of weather modification from a public point of view is not only desirable, but essential. The following reasons may be considered for such analysis:

(1) Present weather modification techniques have a wide territorial scope which makes it impossible to satisfy demands for such modification on a limited, discrete basis. The limits of their incidence appear to be only those of the drainage system or systems within which a given operation is conducted. Some techniques of the future may be even less discrete in their territorial range than those of the present. This means (*a*) that individuals, corporations, or institutions other than the ones primarily interested in the benefits of weather changes will be affected by the procedures used, and (*b*) such benefits as accrue to others cannot be recovered monetarily by the initiators of the project. For example, cloud-seeding operations undertaken for the account of a utility company with hydroelectric facilities will affect the water balance of an entire drainage basin. But since the benefits of precipitation to others are not recoverable by the utility, the scale of operations undertaken may not be the economically appropriate one. Conceivably, the operations might not be undertaken at all because of insufficient direct benefits to the utility, even though reimbursement of benefits to others would make it worthwhile.

Information about these areawide costs and benefits is inadequate at this time. Appraisal of areawide costs and benefits is needed background for decisions on administrative structure, legal regulations, and supporting economic organization for application of these techniques.

(2) The same forces which create benefits to others than those directly financing weather modification also tend to create disbenefits which do not enter directly into the cost-benefit calculations of the individual firm. A form of weather modification which benefits an electric utility company may create disbenefits for a geographically adjacent recreation facility. Similar adverse effects may

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[1] From the author's "Design Study for Economic Analysis of Weather Modification," Advisory Committee on Weather Control Final Report, II, 1957, pp. 235-245. (Some minor revisions are included.)

be created for other enterprises which would have experienced different weather if the modification procedures had not been undertaken. * * *

(3) Several of the economic pursuits which potentially may be benefited most by weather modification are partly public responsibilities. These include transportation services, flood control, hydroelectric power production, irrigation water supply, and municipal services.

Where precipitation is the desired result, the benefits from weather modification will become economically usable mainly through works which must be constructed or maintained at considerable cost, like storage reservoirs or aqueducts. A number of these are within the domain of public administrative interest, both in construction and in operational management. Furthermore, alternative investments or alternative activities yielding the same services as weather modification may be possible. Such may be water recycling, use of saline water (either natural or demineralized), or transportation of water from water-surplus regions to water-deficit regions. Such development also is a matter of public interest.

In view of these facts, the public has a valid interest in research and development of new techniques for supplying these established public services, in the same fashion that a private manufacturer must keep current on new techniques for supplying his products.

In pursuing these studies, analysis of potential benefits and costs will be helpful in deciding upon: (*a*) The extent of public financial support for further experiment. (*b*) Priorities for application of available techniques, both functionally and geographically. (*c*) The design of further physical experimentation.

(4) During the period of continued experiment in the application of weather modification the public should be protected by having available studies assessing total costs and possible or actual composite benefits from these operations. It should not be forced to rely wholly on the sales literature of commercial operators. At the same time studies of composite results should be of interest to the operators themselves. * * *

Design of studies treating the economic effects of weather modification should be undertaken in the light of three distinct levels of weather-control potentiality. Studies can be made of: (1) The economics of near-future practical application; (2) the economic opportunity for the application of known techniques, their refinements, or descendants; and (3) the economic implications of diverting, phasing, or otherwise changing the character and movement of continental airmasses, willfully or involuntarily.

Near-future practical application.—Essentially this would be study of the area within which functionally and geographically known techniques and their probable refinements may be applied. This has been suggested specifically enough in meteorological evaluations of weather control to define this level, although description of their range of application is still somewhat generalized. Within this level, quantitative economic evaluation in some detail appropriately might be sought. The physical techniques here of concern are local modifications of local weather events. They embrace snow and rainfall increases, fog dissipation, hail suppression, and lightning and forest-fire suppression.

Economic opportunity for the application of known techniques.—The second level is that of economic opportunity for the application of known techniques, their refinements, or their technical descendants. This would be the field lying outside the area of application considered practical geographically and functionally for known techniques in the near future. An illustrative component of analysis at this level would be flood damage from continued intensive rainstorms on stationary fronts. The physical techniques concerned would still be local modification of local weather events, but applied over a much wider range of meteorological conditions, and over a wider geographical area than in the first level. Such extension probably depends upon improved knowledge of cloud physics and atmospheric thermodynamics.

Economic considerations related to the character and movement of continental airmasses.—The third level would be the most generalized, and would apply (presumably) to a more distant future than the second level. This is the field within which the effects of far more sweeping mastery over weather events might be achieved. The techniques in this instance differ from those of the first and second levels. They are the possible means of diverting or phasing the great air mass movements directly responsible for many weather phenomena on the earth's surface. They are of hemispheric scope, and truly revolutionary. This, in fact, should be described not as weather modification but as climate modification.

This level of study also might include some appraisal of the range of economic effects to be expected if the presence of radioactive particles, excessive carbon dioxide, and other air-polluting substances physically affect the weather and climate of the country.

The inclusion of this level of study is considered important because of the very great economic effects which would certainly follow revolutionary weather events. The implications for economic policy decision are, of course, profound, and exploration of the economic interrelations involved cannot commence too early.

* * * * *

Desirable objectives of an economic study.—Recognizing a probable need for obtaining conclusive results on a modest budget, for representative coverage, for the treatment of a variety of economic pursuits, and for differentiation of present and potential techniques, several criteria for the selection of analytical procedure are suggested:

(1) Quantified results should be produced. Such results would appear possible for the first and second of the three levels of weather modification potentiality mentioned above.

(2) Results should be representative of as broad an area as possible, within the limits of technical validity.

(3) To the extent possible, results should be easily translatable into public understanding of the potentialities, limitations, and policy problems facing the growth of weather modification.

(4) The procedure should be capable of sifting complex interrelations for net results, avoiding gross benefit-direct cost comparisons.

(5) The procedure should be capable of taking into account institutional modifications of normal economic processes. This is particularly important in the area of water use, and within those parts of the United States where prior appropriation is the water law.

(6) The procedure should be capable of proper appraisal of the multiple effects of weather modification. Again this is of particular importance in the field of water use. Even more than for water development based on natural supplies, the likely benefits depend upon the manner in which the water is used, and the way in which streams are managed to produce the services which water can give. Onsite benefits (and disbenefits) have been relatively easily calculated in previous water development, but it is not certain that the same degree of discreteness will apply to weather control. One important question which must be answered is the extent to which cloud seeding denies water to one geographical area at the same time that it provides it for another. Also, once the water becomes runoff, a definite pattern of use must be assumed, or calculated, for the water, including (in the West) the existing water priority requirements. Ample allowance should be made for the economic effects of conflicting proprietary interest favoring less than optimum total benefits.

(7) Insofar as possible, the procedure should be designed with a view toward continued application, indefinitely, to weather modification problems. As such, it should be flexible, and suitable for application to a geographical unit of any size, and to any economic function. It should be carefully reviewed for adherence to the fundamentals in modern economic analysis.

(8) Insofar as possible, moreover, the procedure should aid in distinguishing those areas of future experiment, operation, legislation, regulation, and other activity suitable for public action, as well as those suitable to the judgments of the marketplace. * * *

The policy value of research on economic implications of weather modification and weather change.—Whether the influence of revolutionary weather changes may be for gain or loss, the full extent of the economic considerations surrounding national or international decisions that may have to be made in the future should be known. They cannot be fully known if they are to be the subject only of overnight emergency appraisals. Accordingly, even though many important assumptions must enter studies of this kind, their substantial value as compared to emergency speculations would seem to weigh heavily in favor of attention to them.

APPENDIX 7

SUMMARY EVALUATION OF KNOWN TECHNIQUES FOR DISCOVERY AND APPRAISAL OF GROUND-WATER DEPOSITS [1]

The succeeding discussion gives a summary evaluation of the effects of certain geophysical and other techniques for locating and appraising ground-water supplies. The techniques include seismic refraction and reflection, resistivity surveys, induced electrical polarization, aerial photography interpretation, resistivity logging, spontaneous potential logging, gamma ray logging and neutron radiation measurement, temperature logging, borehole diameter logging, flowmeter logging, fluid conductivity logging, and the use of radioactive isotopes in appraising natural underground water movement.

Many geophysical methods developed in the last few decades are useful in ground-water exploration and appraisal. There is no single technique which is universally applicable or which provides the basis for obtaining all of the information pertinent in such analysis. Rather, each is limited both in terms of the interpretative results which can be derived from it and with regard to the geologic conditions and other circumstances under which it can be employed. In most instances, the reliability of the information obtained is additive, and it is consequently desirable to employ several techniques simultaneously. Not only is confidence in the results thereby increased, but the range of usable information is augmented. While it can be concluded that there are no serious limitations upon current technical capacity to locate and analyze ground-water occurrences, questions must be raised with regard to the practical availability of these techniques. The prevailing cost of adequate electric logging, for example, may run to about half the average cost of domestic wells. Application of the other techniques also is costly. In almost every instance the equipment must be manned by skilled and experienced personnel; careful comparative studies are then required for practical and reliable results. These costs are amply demonstrated in the experience of prospecting for petroleum, a much more valuable commodity than water in our present economy, per unit of weight or volume.

The costs of prospecting and evaluation are not serious where deposits of large volume, like the deposits of the High Plains, occur at relatively shallow depths (i.e., within 500 feet of the surface of the land). Costs also are not a serious deterrent where there is need for accurate information on the capacity, behavior, and probable life of a large aquifer serving a concentrated demand, as in the vicinity of a large metropolitan area. There is thus little doubt that these techniques of exploration and evaluation will be applied successfully and profitably to the known but incompletely evaluated aquifers. Included among them will be: (1) all from which significant amounts of water are withdrawn to meet metropolitan and industrial water needs; (2) the bolson, alluvial fan, and lava bed aquifers of the West; (3) the Atlantic and gulf coastal plain sediments; (4) the known major aquifers of the Great Plains; and (5) the Mississippi and other alluvial valley sediments of the Eastern States. Planning for the use of these aquifers on a more permanent basis should be possible, almost certainly with the addition of substantial water supplies not now exploited.

Beyond the benefits from more precise definition of the known aquifers of some capacity, the potential additions to our water supply from application of these techniques of exploration and evaluation are doubtful. Their cost makes them of limited value in locating and evaluating low-capacity aquifers which can meet dispersed local demands. At the present time farm and nonfarm rural wells comprise 96 percent of all ground-water installations. A great majority of these, and of the annual new construction, is made up of wells having a daily yield of about 400 gallons. Most of them also are owned by families, and pumped for domestic use. In candor, it must be admitted that dowsing (or "water witching") is still holding its own in the popular mind as a technique of exploration for ground water on this scale. In places, however, the new techniques have been applied successfully in locating even small domestic wells. This has been the case with respect to seismic prospecting in New England. The surface techniques may be of most assistance in this respect because they are the lowest in cost. However, their applicability is almost certain to be geographically limited.

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[1] Adapted from Ackerman and Lof, op. cit., pp. 403–406, with the permission of the Johns Hopkins Press, minor revisions are included.

Rural ground-water use cannot be dismissed as unimportant on the grounds of small installations. About 50 million American people are served by rural and suburban wells. This is 28 percent of the total population of the country.

Perhaps of even greater interest is the capacity of the new techniques to explore for and evaluate water deposits lying deeper within the earth than most of the important known aquifers. Experiences with exploration for and discovery of petroleum illustrate that the technical capacity for such discovery and evaluation certainly can be developed, even if it does not exist at this time. There is little doubt that the physical range of our knowledge and definition of groundwater deposits can be expanded greatly. Although the new techniques may penetrate thousands of feet into the surface structures, there will be some limits to practical interest in the results from their application. The present practical limit in the United States appears to be the maximum depth from which water has been pumped from rest levels for a large-scale use and as a marginal unit of supply. This is about 1,000 feet, as practiced in recent years in the Salt River Valley of Arizona.[3]

Between 500 to 600 feet and 1,000 feet there is ample room for exploration and discovery. Beyond the 1,000-foot depth, however, energy and capital costs of lifting the water to the surface appear to be high enough to make present exploration of limited interest and limited economic importance for agricultural supplies and small-scale wells (e.g., for domestic supply) unless there are further favorable changes in energy costs or the efficiency of pumping equipment. A different situation may be foreseen for productive deep-lying aquifers which could be exploited for municipal and industrial supply. In these latter instances, high exploration and drilling costs can become minor factors if water production is high. Total costs of lifting water even as much as 2,000 feet would not exceed present total water costs in many localities, provided the aquifer can support a well with a-million-gallon-per-day capacity.

The future value of the new techniques may be summarized thus:

(1) They will be of considerable value in delimiting, understanding the behavior of, and defining the characteristics of known aquifers.

(2) The techniques will be of limited value in appraising the small-scale supplies needed to meet additions to dispersed rural demands. Surface techniques may be of some local assistance in such appraisal.

(3) They will be valuable in further exploration for ground water within the future economic range of pumping (probably about 1,000–3,000 feet, depending on productiveness of the aquifer).

(4) The desirability of their use in exploration for deep-lying deposits will vary considerably by region. Further exploitation of ground-water deposits must be weighed against other potential sources of new supply. Throughout the East deep lying deposits may be judged to have little economic significance indefinitely in the future, except in a few localities of extremely intensive demand. Within the West the prospect of desalinization, weather modification, and long-distance transportation of water must be considered as alternatives to use of deep-lying ground water. Competition between desalted sea water, augmented precipitation, and deep ground water may be particularly evident in all the Pacific Coast States. Within the Rocky Mountain States (Idaho, Montana, Colorado, in particular) weather modification promises some cheaper supplemental water. Within the Great Basin and the Great Plains, however, there may be reason for careful assessment of the underlying ground waters, to considerable depth. It is within these regions that the new techniques may have their most important exploratory application in the near future.

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[3] However, greater lifts may be found in other parts of the world. Lifts of 2,300–4,000 feet are reported in Australia, Israel, Northern Mexico, and North Africa. (A. Loehnberg, letter to the author, March 3, 1960.)

APPENDIX 8

WATER BUDGETING AND IRRIGATION[1]

Reuse of water already is common in Western United States irrigation. This type of reuse is not the onsite type being developed within industry, but is the return flow reuse within a watershed. There also may be some recycling of ground water used for irrigation because of deep percolation back to the aquifer from which the supply is being withdrawn. But there appears to be little opportunity for reuse completely within the producing agricultural unit, or farm, in the manner of onsite industrial recirculation. However, the possibility of more efficient techniques of applying water to the production of crops shows promise of assisting water conservation within agriculture. A scheduling technique, water budgeting in irrigation, will be discussed as an example.

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[1] From Ackerman and Löf, op. cit., pp. 442–450. Reprinted with permission of the Johns Hopkins Press.

Deficiences in soil moisture are experienced regularly at sometime in virtually all of the agricultural regions of the United States. Although there are substantial returns to be derived from eliminating or minimizing them, the profitability of using portable irrigation equipment varies greatly with the extent and frequency of these deficiencies. Other factors must be considered in evaluating the practice, such as the availability of suitable supplies of water, pumping costs, and equipment costs. However, the value of irrigation is rapidly being demonstrated for field crops as well as for row crops, and its accelerated use in the humid areas of the country is one of the significant developments in present-day agriculture.

There remains, however, the crucial problem of determining how to make the optimum use of irrigation facilities. To employ them effectively, a farmer needs to know when his crops require additional water, and he has to have some basis for ascertaining how much to apply. While deficiencies of soil moisture seriously limit plant growth, an excess of water also is undesirable. Overirrigation wastes otherwise usable water and causes unnecessary expense; it leaches plant nutrients from the soil, prevents proper soil aeration, and may contribute to erosion.

Agronomists generally agree as to the conditions of available soil moisture which are most conducive to plant growth. There are two "bench marks" or soil-moisture constants which have long been recognized: "field capacity," the maximum amount of water than can be retained against gravity and thus held in storage within the soil profile; and the "wilting coefficient," or permanent wilting percentage. The latter is the soil-moisture content at which the supply in the root zone is so low that plants cannot withdraw water from the soil. Wilting results, and the plants are unable to recover turgidity. Highest crop yields are reported to be obtained when the available soil moisture does not drop below 25 percent nor rise above 90 percent of field capacity.

Although the optimum range of soil-moisture conditions can be identified, the problem of determining the actual moisture conditions of the soil has persisted. Because this task is so difficult in practice, irrigation water is frequently applied in accordance with various rule-of-thumb guides. In many western irrigation districts, for example, irrigation may be scheduled so as to insure the delivery of a specified amount of water to the root zone of the crop each week, irrigation water being used to compensate for the deficiencies of rainfall. However, such a procedure makes no allowance for the changes occurring in water need as the growing season progresses. More often, water is applied when signs of moisture deficiency are recognized in the growing plants. This procedure is also inadequate, for by the time plants begin to show moisture deficiency, they are already suffering and yields have accordingly been depressed.

Irrigation water is used most efficiently when its application is timed so accurately that imminent deficiency of moisture within the soil can be avoided. The time of water need, it follows, must be determined from the actual soil-moisture conditions existing within a particular locality at a given time. Over the years, many techniques of appraising and measuring the moisture content of the soil have been developed. They range from examination of soil samples removed by augers or similar tools, to use of tensiometers of several types,[2] and of instruments employed to detect the speed with which fast neutrons emitted from a radioactive source pass through soil.[3] While several of these instruments have considerable significance as research tools, none appears to be both sufficiently reliable and simple to be of practical assistance to the irrigator.

In recent years an entirely different approach to this problem has been developed, by which commonly available climatological data are employed to determine the occurrence and the extent of deficiencies in the supply of soil moisture available for plant growth. During the last 20 years several variants on this approach have appeared, yielding similar results in practice. The principal differences among the techniques are those converting the climatic data into estimates of soil moisture loss. The better known among the techniques are the Thornthwaite method, the Blaney and Criddle method, and the van Bavel-Penman method.[4] The succeeding description is based on the Thornthwaite method. Dr. Thornthwaite's study of the problem of such conversion is among the longest and most consistently applied in the United States.

Unless there is a large amount of deep percolation, the moisture in the soil can be regarded as a balance between precipitation input, and the outgo in evaporation from the soil surface, transpiration by plants, and runoff. The quantities of water added to the soil can be determined readily through rain-gage measurement, as can runoff through stream gages. If the losses due to the combined effect of evaporation and transpiration can be ascertained with comparable ease, the available supply of moisture in the soil at any time could be determined by means of a simple accounting procedure. The resulting information regarding soil-moisture conditions can then be used to schedule irrigation, water being applied in an amount sufficient to bring soil moisture back to the optimum level whenever it becomes significantly depleted.

The first step in the water budget technique is to calculate the amount of water that would be transferred from the soil to the atmosphere by evaporation and transpiration if abundant moisture were constantly available in the soil for the use of vegetation. This is potential evapotranspiration, in contrast to the moisture actually transferred by evaporation and transpiration. The rate of actual evapotranspiration depends upon five factors: weather, supply of soil moisture, plant cover, soil type and structure, and land management. However, the amount of potential evapotranspiration is estimated by analysis of only two climatic factors, the intake of solar radiation by plants and the soil surface, and to a lesser extent the temperature of the layer of air adjacent to the soil surface.[3] By use of an empirical formula, the changing rate of potential evapotranspiration throughout the year may be computed for any locality for which temperature records are available. Comparison of the amount of actual precipitation with the changing rate of potential evapotranspiration through the seasons will then indicate the amount and the time of soil-moisture surplus and soil-moisture deficiency.

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[2] Tensiometers measure the electrical resistance of soils, which varies with their moisture content.

[3] H. R. Haise, "How to Measure the Moisture in the Soil"; "Water," the Yearbook of Agriculture, 1955, U.S. Department of Agriculture, Washington 1955, pp. 362–371.

[4] C. W. Thornthwaite and J. R. Mather, "The Water Budget and Its Use in Irrigation"; "Water," the Yearbook of Agriculture, 1955, pp. 346–358; H. F. Blaney and W. D. Criddle, "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data" (Technical Publication 96), U.S. Department of Agriculture, Soil Conservation Service, Washington, 1952; C. H. M. van Bavel, "Estimating Soil Moisture Conditions and Time for Irrigation With the Evapotranspiration Method," U.S. Department of Agriculture, Agricultural Research Service, and North Carolina Agricultural Experiment Station, Soils Department, Raleigh, N.C., 1957 (revised). Van Bavel has recently published several descriptions of the regional application of his method; e.g., C. H. M. van Bavel and J. J. Lillard, "Agricultural Drought in Virginia" (Technical Bull. 128), Virginia Agricultural Experiment Station, Department of Agricultural Engineering, and U.S. Department of Agriculture, Agricultural Research Service, Blacksburg, Va., 1957.

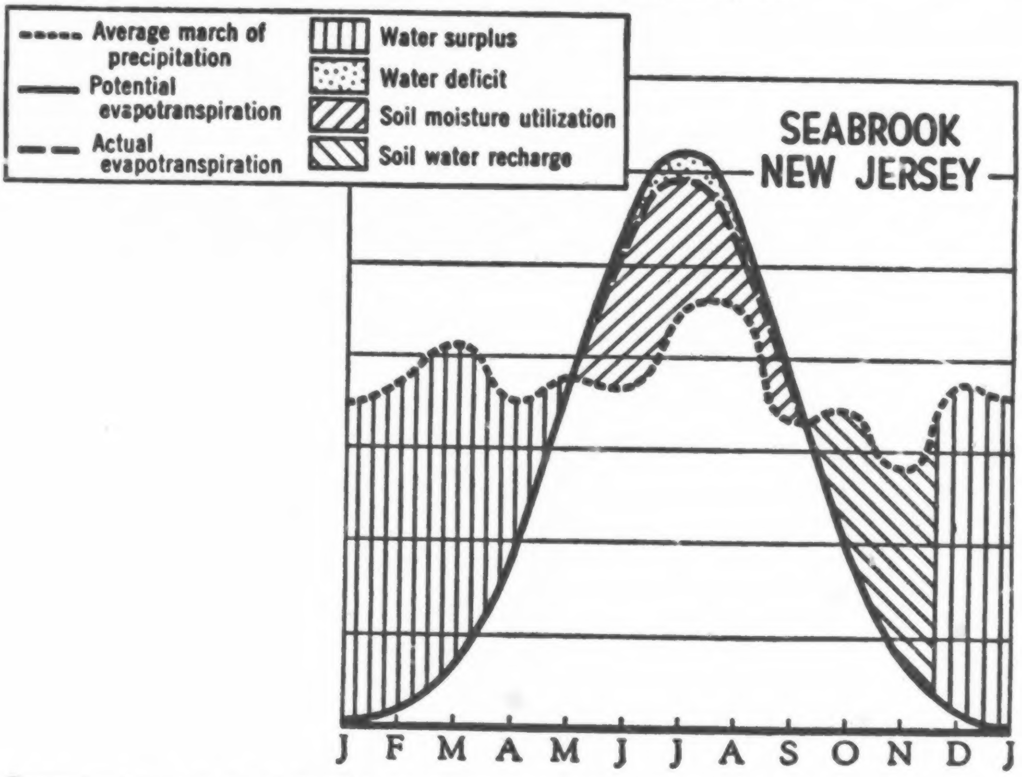

FIGURE I.—Annual march of precipitation and potential evapotranspiration at Seabrook, N.J. (From Ackerman and Löf, *op. cit.*, page 446.)

Although its application is subject to some uncertainties, the concept of potential evapotranspiration is proving to be a useful analytical tool. Because the rate of actual evaporation and transpiration is limited by the supply of moisture available in the soil, at sometime during the year it is almost certainly less than the rate of potential evapotranspiration, the amount of the difference indicating the extent of the soil-moisture deficiency. The situation in various parts of the country has been represented in synoptic form by Thornthwaite in what he calls the annual march of precipitation and potential evaporation (fig. I).

At Seabrook, N.J., the potential evapotranspiration is negligible during the winter months, but it rises rapidly in the spring, reaching a peak of more than 6 inches in July, and then declining sharply in the autumn. The occurrence of precipitation is far more evenly distributed throughout the year. It can thus be seen that a water deficit occurs during the summer months in this area, while in the autumn water need falls below precipitation. After the excess rainfall has replaced the soil moisture previously used, a water surplus is experienced.

When the soil moisture is at field capacity, actual and potential evapotranspiration are equal, and the amount of precipitation in excess of the potential evapotranspiration rate then serves either to raise ground water levels or is released as surface and subsurface runoff. When the potential evapotranspiration rate becomes greater than precipitation the following spring, soil-moisture storage is drawn upon for actual evapotranspiration. However, the soil becomes progressively drier during the summer months. When the moisture content reaches a point where water is no longer available to plants in an amount necessary for optimum growth, actual evapotranspiration becomes less than potential evapotranspiration. This is the water deficit.

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[3] See C. B. Tanner, "Factors Affecting Evaporation From Plants and Soils," Journal of Soil and Water Conservation, 12 (1957), 221-227. "• • • We should look for those factors which affect the latent heat exchange at the surface. This is evapotranspiration."

* * * * *

This general procedure can be used as a practical aid in scheduling irrigation. Actual daily climatological values are employed to evaluate soil moisture conditions instead of monthly means of temperature and precipitation. A day-by-day inventory of the moisture in the soil can then be maintained by a simple accounting procedure in which the losses through evapotranspiration are debited and the additions through precipitation during the growing season are credited. The starting point for the "moisture account" may be taken as the soil moisture present at the beginning of the growing season for the particular crop. This may be at "field capacity," a condition when the soil contains no surplus of gravitational water and no deficit of capillary water. If precipitation occurs when the soil is at field capacity, the additional supply of moisture is rapidly lost by downward percolation, or lateral movement. The length of time surplus water is retained depends upon the amount of water and permeability of the soil. In the absence of precipitation, withdrawals from the balance begin to occur as the store of soil moisture is depleted by evaporation and transpiration. At this time, the amount of actual and potential evapotranspiration is the same. The balance is decreased by the amount of moisture loss, computed by a formula for potential evapotranspiration. When the soil begins to dry out, it becomes progressively more difficult for additional water to be expended by evaporation and transpiration.

* * * * * * *

The methodological basis of this technique for maintaining a daily water budget has here been outlined, but in practice the procedure has been simplified by the preparation of irrigation guides or tables for different localities which facilitate determination of the withdrawals from the soil moisture balance under varying moisture conditions. The resulting information is then employed directly in fulfilling an irrigation schedule. (Fig. J.) This schedule indicates the amount of moisture to be applied to the soil and the timing of the application so that soil moisture deficiency does not drop below undesirable levels. As practiced, this technique of irrigation depends not only on water balance calculations, but also on consideration of root depth of the crop being grown, soil type, and the economic and technical feasibility of irrigation practice. Irrigation water is applied whenever the soil moisture balance becomes depleted to the predetermined significant level, the water "inventory" thereby being increased by the appropriate amount. Shallow-rooted crops must be irrigated more frequently, but require smaller amounts of water than deeper rooted pastures or orchards. The growth cycle of the crop is also a factor. Even under the same solar and temperature conditions, actual evapotranspiration varies with the changing moisture needs of a plant as it grows. An irrigation schedule should therefore be adjusted or compensated for these changes in water requirements.

* * * * * * *

The use of an irrigation scheduling technique can affect the productive employment of water wherever it is applied to crops. It is clear that a relatively accurate estimate of the course of evapotranspiration, and its relation to the scheduling of water application, will be of interest in both eastern and western United States. However, the technique is of special interest in the East. The reason lies in the nature of water deficiencies in the two major geographical divisions of the country. The irrigated West is characterized by recurring seasonal deficiencies, with very little and uncertain supplies of moisture from the atmosphere during the growing season. In this situation irrigation may be planned on a seasonal basis, once the water requirements of the crop are known. It is likely that a fair adjustment already has been made in western irrigation areas between the water applied to crops and the potential evapotranspiration. Thornthwaite reported in 1953 a very close correspondence between the observed consumptive use in 12 western irrigation areas and the computed potential evapotranspiration[6]

This does not mean an absence of overwatering in the West, for there are instances of applying larger amounts of water than needed by crops. However, this is known to be related in many cases to the need for preventing an accumulation of salts in the soil.

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[6] C. W. Thornthwaite, "The Place of Supplemental Irrigation in Postwar Planning," Laboratory of Climatology Publications in Climatology, vol. VI, No. 2, Seabrook, N.J., 1953, pp. 18–19.

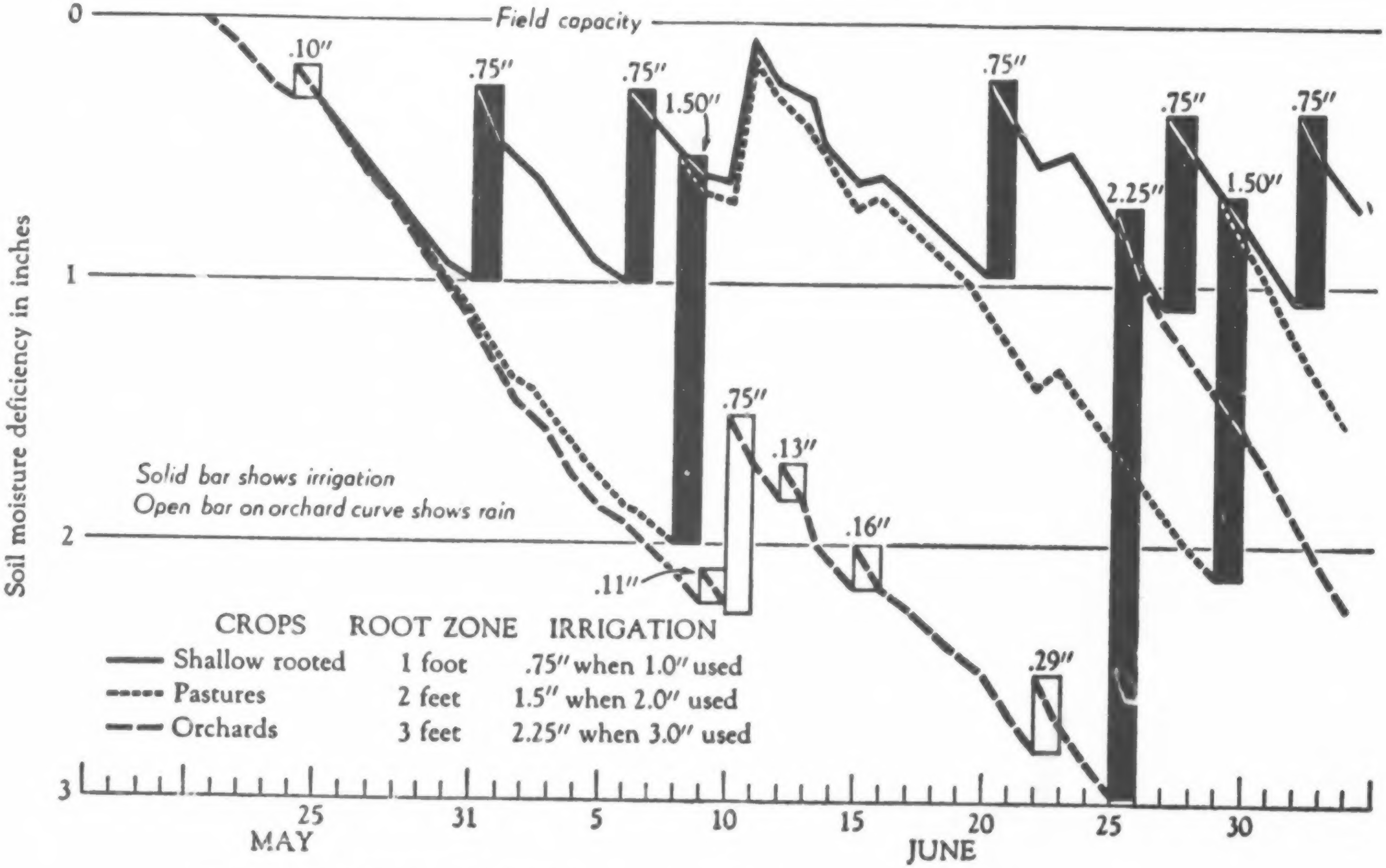

FIGURE J.—Typical irrigation schedule in humid eastern States. (From Ackerman and Löf, *op. cit.*, page 440.)

APPENDIX 9

THERMAL-ELECTRIC GENERATION CORRELATION OF EFFICIENCY WITH SIZE OF UNIT AND SIZE OF PLANT

Total costs of generating a kilowatt-hour of electricity in thermal plants vary with a number of factors, including age and design characteristics of equipment. The following data are intended to represent as nearly as possible some of the relations of size of generating unit and size of individual plant with efficiency. It is recognized that these data are highly generalized and that local factors may cause considerable variation in the quantitative results here indicated. For example, local temperatures of cooling water influence efficiency. However, in spite of these variations, the correlation between size and degree of efficiency is still very clear. Perhaps the best quantitative indication is that of the comparative net heat rates of generators of different sizes. This is given in the following table:

Typical net heat rates, thermal-electric generators, 5,000–450,000 kilowatts

Generating capacity of unit, in megawatts:	*B.t.u.'s per net kilowatt-hour* [1]
5	15, 500
8	15, 200
13	13, 250
22	12, 500
33	12, 200
44	11, 500
50	10, 300
75	10, 000
100	9, 700
125	9, 500
150	9, 300
200–250	9, 200
300–335	9, 000
450	8, 500

[1] H. E. Roberts, "Trends in Power Generation: Lessons for Nuclear Engineers," Nucleonics, vol. 16, No. 7 (1958), pp. 76–79.

For operation and maintenance costs, the biggest relative gains in efficiency can be achieved by increasing the size of generating unit. Although some gains may be attained with multiple-unit plants, they do not affect operation and maintenance costs nearly as much as size of generating unit. This is apparent from the following data provided by Roland A. Kampmeier, assistant manager of power of the Tennessee Valley Authority:[1]

Typical thermal electric generator operation and maintenance costs per kilowatt-hour, excluding fuel

[In mills]

	1-unit plant	4-unit plant
Unit size, megawatts:		
65	1. 0	0. 7
125	. 5	. 4
500	. 33	. 3

For fixed plant costs the reverse is true. Considerable savings may be achieved through plant construction of multiple units. A number of costs are approximately the same regardless of the size of plant. These would include land and land rights, access to road or railroad, service and office structures, unloading, crushing and storage facilities, and station maintenance equipment. Planning, geological explorations, plant design, model tests, site planning, and review also may be considered relatively fixed costs. Cost of this type represent about 25 percent of total plant investment for a one-unit plant as compared to about 10 percent of total costs for a four-unit plant.[1]

The influence of both types of costs as correlated with size is illustrated in the data presented by Nucleonics.

Approximate generating costs of 3 thermal electric generating plants [1]

	Plant A	Plant B	Plant C
Number of generating units	4	4	4.
Unit size, megawatts	5–15	33	150–200.
Plant cost per kilowatt capacity.	$200–$250	$160–$200	$130–$150.
Operating pressures (pounds per square inch).	600	850	2,000.
Operating temperatures	825° F	900° F	1,000–1,050° F.
B.t.u.'s per net kilowatt-hour	14,000	12,300	9,200.
Plant factor	80 percent	80 percent	80 percent.
Total costs per kilowatt-hour at long-run plant factor of 60 percent.	11 mills	9 mills	6.6 mills.

[1] H. E. Roberts, op. cit.

Another indication of total production expenses is given in the curves presented for single- and multiple-unit plants using 100-megawatt and 225-megawatt units compiled by the Tennessee Valley Authority from data given to the Federal Power Commission's "Steam-Electric Plant Construction Cost and Annual Production Expense—1957" (fig. K).

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[1] Personal communication from Mr. Roland A. Kampmeier, Tennessee Valley Authority, November 1959.

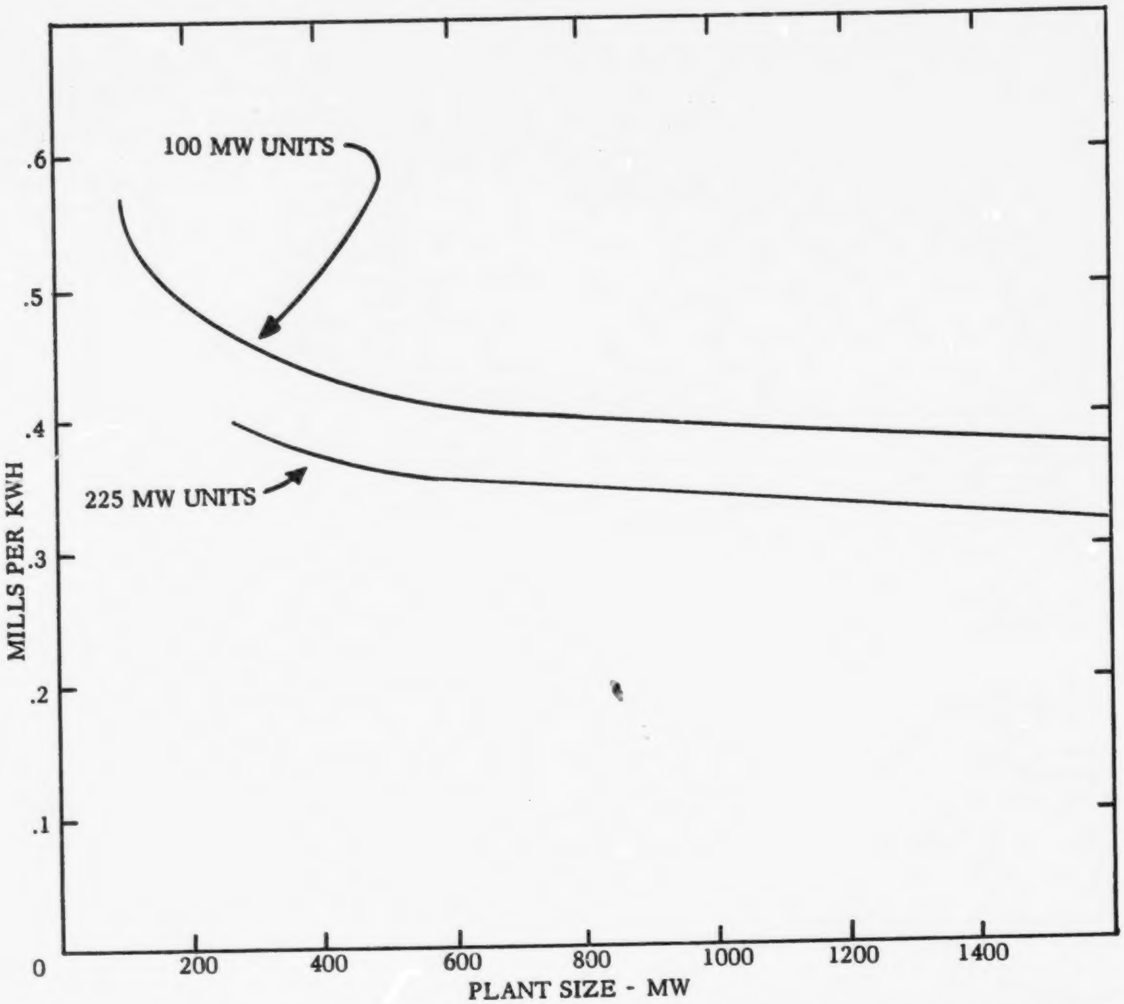

Figure K.—Total production expenses (excluding fuel) of 100 and 200 megawatt thermal electric generating units compared to plant size, based on 800 hours' use, 1957. (Tennessee Valley Authority, Office of Power, 1959.)

Appendix 10

The Use of Nuclear Explosives in Water Resource Development

(By Donald Patton)

Nuclear detonations for purposes of water resource development are among the important peaceful potential applications of nuclear energy. The possible use of nuclear explosives for excavation, earth moving, and other applications in industry has already received considerable attention. Much of the present data relating to possible industrial uses of nuclear energy have been developed as a byproduct of weapons-development programs at the Nevada test site of the Atomic Energy Commission, but many lines of investigation are only in their initial stages.

The possibilities and problems of applying nuclear energy to water development projects will be considered in general terms from three standpoints: the engineering possibilities of nuclear explosives: cost comparisons between nuclear and conventional explosives; and the heat, blast, and radiation containment problems.

ENGINEERING ASPECTS

Nuclear explosives are capable of performing a wide variety of engineering operations. Application of nuclear explosives to large-scale excavations for dam and reservoir construction should be entirely possible. Other types of potential applications include the removal of silt accumulated in a reservoir.[1] Promising engineering applications of nuclear energy reside not only in the large scale of instantaneous energy release possible but also in the fact that, unlike ordinary detonations, earth and rock materials are both fractured and removed as a result of the blast. A single 100 kiloton detonation,[2] for example, should be able to excavate approximately 6.5 million cubic yards of material. The earth removal features of nuclear explosives are thus a key aspect of the potential application of this form of energy in future water resource development. On the other hand it should be noted that in order to perform a given operation while minimizing the radiation hazard from a nuclear device it would often be necessary to fracture and excavate a larger cubic volume than necessary for construction purposes alone.

One other possible engineering application is in fracturing deep formations to increase permeability and water storage capacity. Conceivably, substantial underground storage capacities could be provided by nuclear blasting, where none exist now.

COST ASPECTS

Sufficient data are now available on the costs of surface and subsurface nuclear explosions to permit general comparison with costs of conventional explosives and earth movement operations. Bacigalupi gives estimated excavation costs per cubic yard with the use of nuclear devices as follows: 10 kiloton, $0.64; 100 kiloton, $0.12; 1,000 kiloton, $0.02.[3] In general, nuclear devices become competitive with conventional means of earth removal and earth fracturing at points between yields of 10 and 100 kiloton, depending on site characteristics and other factors. Simultaneous detonations of nuclear devices from several points as part of a single operation increase the fracturing and removal accomplished per unit of energy released, permitting some reductions in unit costs. Approximate costs for a 10 kiloton detonation at present prices are about $500,000; for a 1,000 kiloton device costs per detonation would be only about twice as great, while volume of removal would approach close to 70 times as great.[3] [4] Thus comparative cost favor nuclear materials at higher energy yield levels.

HEAT, BLAST, AND RADIATION EFFECTS

Future timing and extent of application of nuclear explosives will depend primarily on the progress which can be made in the reduction of heat, blast, and particularly radiation hazards associated with nuclear detonations. This latter aspect of nuclear energy is the principal deterrent to its use in the immediate future for water resource development. Studies undertaken to date, however, indicate that problems of containment are not insoluble. The development of means of neutralizing nuclear hazards in engineering operations well before 2000 appears to be a definite possibility.

In the use of nuclear explosives for engineering purposes, much of the work would be accomplished by comparatively deeply buried shots. Heat wave release into the atmosphere as a result of a nuclear detonation decreases rapidly with increasing depth at which the explosion takes place, and energy release in the form of heat is not expected to be a major problem. Likewise surface blast effects and reflected ionosphere blasts will be of minor importance in buried explosions. Seismic shock may present a problem in instances of larger energy releases.[5]

Nuclear detonation hazards center mainly in radiation hazards. Three types of radiation hazard must be considered: fallout, fission products trapped in the excavated area, and induced radiation in surrounding materials as a result of neutron capture. Several aspects of radiation hazard reduction already appear promising. Fallout can be confined to a small area or reduced to negligible proportions with more deeply buried detonations, but fallout from shallow explosions is almost as great as from surface shots. Residues of fission products in the detonation area may be reduced by further decreases in the fission-fusion ratio in nuclear devices. These ratios have declined substantially since the first nuclear explosions.[6] Use of boron cappings on nuclear devices to capture neutron particles before induced radiation occurs in surrounding materials has been suggested.[6] Postdetonation studies at the Nevada test site have also revealed that 60 percent to 85 percent of the gross radiation product was contained by glass (silica) present in the particular substrata after the explosions.[7] Studies in the reduction of radiation hazards in peaceful uses of nuclear explosives have only begun, and other aspects of radiation containment may emerge as work progresses. The problems appear formidable but far from insoluble.

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[1] Luke J. Vortman, "Earth Moving With Nuclear Explosives," in "Industrial Use of Nuclear Explosives," University of California, Lawrence Radiation Laboratory, Plowshare Series, Report No. 1, September 1958, pp. 45–46.

[2] TNT equivalent.

[3] Clifford M. Bacigalupi, "Large Scale Excavation With Nuclear Explosives," University of California, Lawrence Radiation Laboratory, January 1959, p. 11.

[4] Gerald W. Johnson, "Mineral Resource Development by the Use of Nuclear Explosives," University of California, Lawrence Radiation Laboratory, February 1959, p. 7.

[5] Bacigalupi, op. cit., pp. 8–9.

[6] Johnson, op. cit., p. 3.

[7] G. W. Johnson, G. H. Higgins, and C. E. Violet, Underground Nuclear Detonations," University of California, Lawrence Radiation Laboratory, July 1959, p. 17.

APPENDIX 11

THE APPLICABILITY OF COMPREHENSIVE DEVELOPMENT TO THE WATER PROBLEMS OF THE NINE SOUTHWESTERN STATES, 1960–2000

The existence in 1960 of water supply problems of varying degrees of severity in the nine Southwestern States already is common knowledge to members of the committee. In addition, there appears to be conviction that these problems will continue and perhaps intensify during the entire period 1960–2000. There is little question that heavy expenditure for water supply facilities will have to be made in these States if their growth potentialities are to be realized, and little doubt that water development effort will have to be accelerated. The major questions instead relate to the form which development is to take. What pattern of public activity is likely to bring the highest level of income for the most people within the level of public expenditure chosen, whatever the appropriation level? What emphasis should be placed on research and experiment? What kind of construction will be needed? What will the objectives of efficient water management be?

One major conclusion of this report is: A pattern of comprehensive development as described herein will increase the efficiency of water development in the Southwestern nine States, and may even be mandatory in the 1960–2000 period. This appendix gives the author's reasons for that conclusion.

The Geological Survey, in a report to the committee,[1] lists six major water problems as occurring within the United States: supply, distribution, quality, pollution, flood, and variability. All six are encountered in the nine Southwestern States, the only major area of the country being so distinguished. Moreover, six of the eight different types of quality problems are to be found in various districts of these States. They are: silt, industrial wastes, irrigation return flow, time variation in dissolved solids content, sea water intrusion into aquifers, and hardness.

THE SUPPLY PROBLEM

The basic problem of the Southwest is quantity of supply. It will be discussed briefly here. It is not easily evaluated, for the basic data at hand do not allow a consistent approach, and the preparation of a sophisticated statistical analysis is a task exceeding the resources available for this study. Estimates of the mean runoff for the period of record by State are available, but these data do not provide the best basis for evaluation or planning. For these States arithmetic means may be skewed upward by unusually wet years of infrequent occurrence, years which have little value for regulation. Among the simpler measures, the median runoff (middle item in a statistical series) is more likely than the arithmetic mean to strike the average of most value to planning of regulation. Yet such data are available for only a few stations in each State. Moreover, even the means are difficult to evaluate in the face of sometimes conflicting and often incomplete data. An example is given in the available data on runoff for the State of Texas (table C), which are more complete than some. The succeeding evaluation is based upon hydrologic data of this type, and is subject to their limitations.

The mean annual runoff for the nine States is 196 million acre-feet.[2] More than one-third of this occurs within the State of California. Based on an arbitrarily chosen sample and extrapolation, a rough estimate of the median annual runoff is 150 million acre-feet. Withdrawal of water for irrigation and all other purposes in 1955 was about 83.7 million acre-feet.[3] Although it is difficult to estimate, water disappearance (consumptive depletion) was thought to be about 48 million acre-feet.[3] Total 1955 population of the States was 30 million. Per capita withdrawals thus were about 2,475 gallons per day, for all purposes, including irrigation. (Table D.)

TABLE C.—*4 estimates of stream runoff in Texas*

[Thousand acre-feet]

Year	I. U.S. Bureau of Reclamation [1]	II. Texas Board of Water Engineers [2]	III. U.S. Geological Survey, Water Resources Division [3]	IV. Estimates for entire State [4]
1924	32,301			
1925	4,611			
1926	30,309			
1927	22,055			
1928	11,975			
1929	24,474			
1930	18,729			
1931	19,558			
1932	33,564			
1933	16,193			
1934	15,917			
1935	33,017			
1936	19,997			
1937	18,824			
1938	27,588			
1939	10,533			
1940	14,938	50,263		
1941	53,648	82,536		
1942	33,925	52,832		
1943	13,429	24,182		
1944	30,422	56,534		
1945	39,974	73,314		
1946	34,005	75,746	62,000	79,360
1947	29,250	38,637	51,500	65,920
1948	14,395	25,520	28,200	36,096
1949	16,284	42,430	31,600	40,448
1950	26,929	49,592	54,200	69,376
1951		17,017	14,500	18,560
1952		22,252	19,400	24,832
1953		35,404	35,700	45,696
1954		15,984	15,600	19,968
1955			17,400	22,272
1956			11,000	14,080
1957			57,200	73,216
Mean	[5] 23,957	[6] 44,150	[7] 38,954	[7] 49,910

[1] U.S. Bureau of Reclamation, "Water Supply and the Texas Economy," U.S. Senate, 83d Cong., 1st sess., Document No. 57. Washington, D.C., 1953, p. 59. Runoff excludes Rio Grande and portion of Sabine. Combined runoff is for Sabine, Neches, Trinity, San Jacinto, Brazos, Colorado, Guadalupe, San Antonio, and Nueces Rivers at gaging points approximately 100 miles inland from gulf coast, at 300-foot contour.

[2] Texas Board of Water Engineers, "Inventory of the Surface Water Resources of Texas," graph opposite p. 16. All Texas runoff including 50 percent of Rio Grande, 50 percent of Red River plus all of Sabine above Logansport plus 50 percent of inflow into Sabine below Logansport.

[3] Does not include Rio Grande or Red River runoff.

[4] Includes 50 percent of Rio Grande runoff, 50 percent of Red River runoff, and all of Sabine River runoff. Estimates for individual years 1946–57 computed at 128 percent of col. III. Mean computed by the U.S. Geological Survey.

[5] 1924–50.

[6] 1940–54.

[7] Long-term mean computed by the U.S. Geological Survey.

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[1] Water Resources Division, U.S. Geological Survey, "National Water Problems," Washington, D.C., 1959.

[2] Ackerman and Löf, op. cit.

[3] Ackerman and Löf, op. cit., tables 6 and 11.

TABLE D.—*Some basic data for evaluating water requirements in the Southwestern States, year 2000*

	Mean runoff	1955, irrigation withdrawal	1955, other withdrawal	1955, total withdrawal	1955, population	2000, Bureau of Census series II-1 projection	Possible total water withdrawal, year 2000
	Million acre-feet per year	*Million acre-feet*	*Million acre-feet*	*Million acre-feet*	*Thousands*	*Thousands*	*Million acre-feet*
Arizona	4.25	7.75	0.33	8.08	980	4.218	
California	71.94	25.81	8.61	34.42	13,032	45,107	
Colorado	22.80	7.07	.87	7.94	1,549	4,482	
Kansas	12.29	.83	1.68	2.51	2,060	4,074	
Nevada	3.54	2.15	.14	2.29	225	1,015	
New Mexico	3.89	2.82	.18	3.00	795	2,278	
Oklahoma	19.02	.25	.84	1.09	2,168	3,141	
Texas	49.91	11.47	7.78	19.25	8,563	22,656	
Utah	8.15	4.67	.49	5.16	781	2,313	
Total	195.79	62.82	20.92	83.74	30,153	89,284	160
Estimated mean annual runoff, driest 10-year period, 9 States	156						
Estimated median annual runoff, 9 States	150						
			Gallons per day	*Gallons per day*			*Gallons per day*
Per capita withdrawal, 9 States			617	2,475			1,600

Should this level of use be continued to the year 2000, and a high-range population projection for the nine States be used (89.3 million),[4] annual water requirements would be on the order of 250 million acre-feet, and disappearance on the order of 125 million acre-feet. Should the level of per capita use be only the same as the national level suggested for 2000 (about 1,600 gallons per capita per day),[5] total requirements would be 160 million acre-feet.

If a still lower consumption level is chosen, with per capita levels considerably below the 1,600 gallons per day national per capita requirement projected for 2000, total annual withdrawal requirements for the nine States would be 140 million acre-feet. This estimate is based on the U.S. Department of Agriculture projections of irrigation for the year 2000 within the nine States,[6] and the same level of nonirrigation water consumption as in 1955 (about 617 gallons). In view of a much increased proportion of industrial water use for a population of 89 million as compared to the present, this probably is an unrealistically low level, assuming present use practices.

Domestic and municipal requirements may be expected to remain about the same as at present, if illustrative past-term trends in municipal consumption are to be taken as indicators (fig. L).

The mean or median runoff for a 25-year or longer period, as used above, does not tell the entire story of water availability. The precipitation receipts of the Southwest, like other regions of low rainfall, show a wide amplitude in annual fluctuation. The averages of even a decade's runoff may fall notably below the median of the longer record (table E). The driest 10-year average runoffs of Texas, New Mexico, and Nevada are only about two-thirds of the median. The weighted average for the nine States is 80 percent of median runoff in the driest 10-year period. For eight States, excluding California, it is 67 percent. Thus the average runoff for the nine States over their driest 10-year periods may be only about 120 million acre-feet, well below the lowest estimate of requirements for a population of 89 million (140 million acre-feet). If the driest 6-year period is considered, the average falls still lower, to about 63 percent of the estimated median, or a probable total of 94.5 million acre-feet. In Texas, the 6-year period of 1951–56 brought only 46 percent of the estimated median runoff.

TABLE E.—*Average annual runoff during driest 6-year period and driest 10-year period and runoff of driest single year between 1921 and 1959, as a percentage of normal runoff, 9 Southwestern States* [1]

State	Driest single year	Percentage of normal	Driest 6 years	Percentage of normal	Driest 10 years	Percentage of normal
Arizona	1956	33	1943–48	74	1950–59	76
California	1931	41	1929–34	69	1926–35	83
Colorado	1954	49	1951–56	81	1946–55	87
Kansas	1956	[2] 10	1953–58	67	1931–40	82
Nevada	1931	18	1926–31	60	1926–35	66
New Mexico	1951	32	1951–56	53	1950–59	64
Oklahoma	1939	26	1951–56	59	1931–40	77
Texas	1925	21	1951–56	46	1947–56	66
Utah	1934	35	1931–36	75	1931–40	79
9 States (weighted)				63		80

[1] Median runoff of the base period 1921–45.

[2] Only 1 station in the State reported for the year. Eastern half of State is shown as having less than 25 percent of normal runoff.

Source: Computed from data contained in Water Resources Review, published annually by the U.S. Geological Survey. Generalized by State on the basis of 1 or more key gaging stations in each State.

For all water requirements depending directly or indirectly on runoff the possibility of bridging drought periods by reservoir storage may be considered. Could an annual supply equal to the normal runoff be obtained by construction of sufficient storage capacity? This possibility may be evaluated somewhat be considering the hydrologic situation of the State of Texas. Texas mean runoff is about 50 million acre-feet annually. Total water withdrawal requirements for the year 2000 could reach 39 million acre-feet, calculated from the series II-1 population estimate of 22 million and the estimated 1,600-gallon daily national average consumption of 2000. Could adequate storage maintain an annual supply equal

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[4] Bureau of the Census series II-1.

[5] Resources for the Future, Inc., Annual Report, 1959, pp. 72–73.

[6] U.S. Department of Agriculture," Land and Water Potentials and Future Requirements," Washington, D.C., 1959.

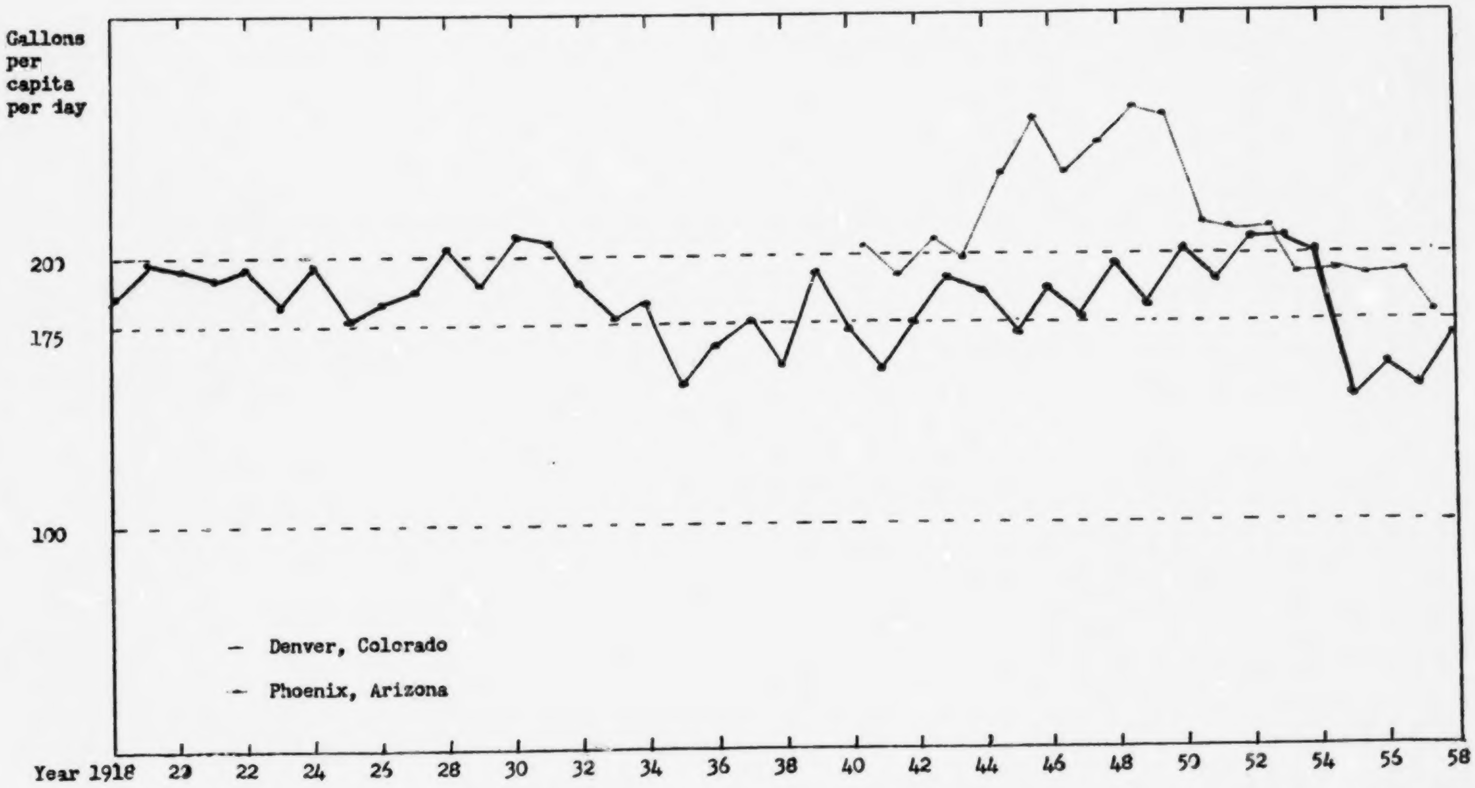

FIGURE L.—Per capita water consumption from municipal systems, Denver, Colorado, and Phoenix, Arizona. Sources: Statistical data from Phoenix Department of Water and Sewers, and city of Denver.

to the total requirements, thus estimated, during the driest period of record? The answer appears to be "No."

The driest 10-year period of record in Texas was the period 1947–56, when the mean estimated runoff for the period fell to about 35.7 million acre-feet and the median of the period was 30 million. For the 6-year period 1951–56, the mean was reduced to 24.2 million acre-feet table F). At the end of 1956 the cumulative departure from the long-term mean runoff in the State over 9 years was −156.8 million acre-feet. Such a deficit could not be met by storage, even if enough capacity were constructed to provide the maximum obtainable regulation for the State, following Langbein's regulation-capacity ratios and the Bureau of Reclamation estimates of average evaporation losses for western reservoir storage.[7] The maximum obtainable regulation would be reached with about 150 million acre-feet of storage, which would net (because of evaporation losses) only about 113.5 million acre-feet of releases during a 9-year period. Thus storage alone could not meet the postulated withdrawal requirements of 2000, even though the total storage capacity were increased to eight times that of the present (18.8 million acre-feet in 1954) (table G).

TABLE F.—*Estimated runoff in Texas, 1946–57, and cumulative departure of precipitation*

	Runoff [1]	Annual departure from long-term mean	Cumulative departure	Cumulative departure of precipitation, from mean [1]
1946	79.4			
1947	65.9			
1948	36.1	−13.8	−13.8	−31
1949	40.4	−9.5	−23.3	−81
1950	69.4	+19.5	−3.8	−64
1951	18.6	−30.3	−34.1	−11
1952	24.8	−25.1	−59.2	−61
1953	45.7	−4.2	−63.4	−100
1954	20.0	−29.9	−93.3	−215
1955	22.3	−27.6	−120.9	−265
1956	14.0	−35.9	−156.8	−398
1957	73.2	+23.3	−133.5	−249
Long-term mean	49.9			
Mean 1947–56	35.7			
Median 1947–56	30.5			

[1] Millions of acre-feet.

Source: Table C, col. IV and data prepared by the U.S. Geological Survey, Water Resources Division for the U.S. Senate Select Committee on National Water Resources.

TABLE G.—*Usable reservoir storage capacity,*[1] *9 Southwestern States, Jan. 1, 1954*

	Usable storage acre-feet
Arizona	33,246,800
California	17,700,900
Colorado	3,826,700
Kansas	4,008,700
Nevada	673,300
New Mexico	3,530,700
Oklahoma	10,248,400
Texas	18,852,900
Utah	2,053,200
Total 9 States	94,101,600

[1] Capacity in reservoirs of 5,000 acre-feet or more.

Source: U.S. Geological Survey, Water Resources Division.

These estimates are admittedly rough and subject to verification, but they do provide information of some value in assessing a pattern of water development in Texas and the other Southwestern States. The following conclusions seem reasonable:

(1) The situation described for Texas may be considered roughly typical for at least six other Southwestern States. Only California and Colorado, with partly different runoff patterns, would be likely to show more certainty of bridging drought periods by storage releases to meet requirements in the pattern assumed above.

(2) A vast program of water regulation would be necessary to meet a 1,600-gallon per capita daily withdrawal requirement for 89 million people in the 9 States. The already high per capita ratio of storage capacity in these States (3.1 acre-feet in 1954) [8] would have to be almost doubled. Total storage in the amount necessary to bridge drought periods would be on the order of 525 million acre-feet. At 2.7 times the average estimated annual runoff this again approaches the theoretical maximum regulation possible on these streams. It means also that many of the later increments to regulation would be achieved at very high cost. In other words, the prospect of meeting a 1,600-gallon per capita daily requirement from surface-water receipts for the series II–1 population of the year 2000 would bring these States face to face with very high-cost water in preparing for anticipated requirements.

It may be noted that the actual future withdrawal requirements, as estimated, do not necessarily place an equivalent demand upon flow or storage releases. Return flow from irrigation, sewage and industrial effluent, and cooling-water discharges all can return to stream courses or aquifers water that can be reused downstream or in local subsequent withdrawals. In most parts of the Southwest, however, there is a limit to such reuse because of the ever-increasing load of dissolved solids added to water so used, particularly in low-flow years. High dissolved solids content is a handicap of many southwestern waters, even as they occur naturally. Reuse intensifies this handicap because of evaporation, or because of flow through the many saline soils of the region. It could easily make much water unusable at the level of use required by the projected 2000 population. For the Southwestern States as a whole it is almost axiomatic that a high degree of regulation will be sought so as to maintain quality during low-flow periods, unless this problem can be [illegible] in other ways.

Accordingly, it will become profitable to these States and to the Federal Government: (*a*) to achieve efficiently the large amount of needed regulation (at the lowest cost which can provide the benefits anticipated); and (*b*) to examine and exploit other means of matching supply and requirements in addition to flow regulation. This may be done by controlling economic growth, reducing requirements, exploiting new supplies, improving water of substandard quality, and other measures.

The first of these alternatives, controlling economic growth, is not one that the region or the Nation should wish to consider. The other alternatives include all of the elements of comprehensive development, as defined in this report.

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[7] Langbein op. cit., Geological Circular 409.

[8] Average for the United States, 1.17 acre-feet in 1955.

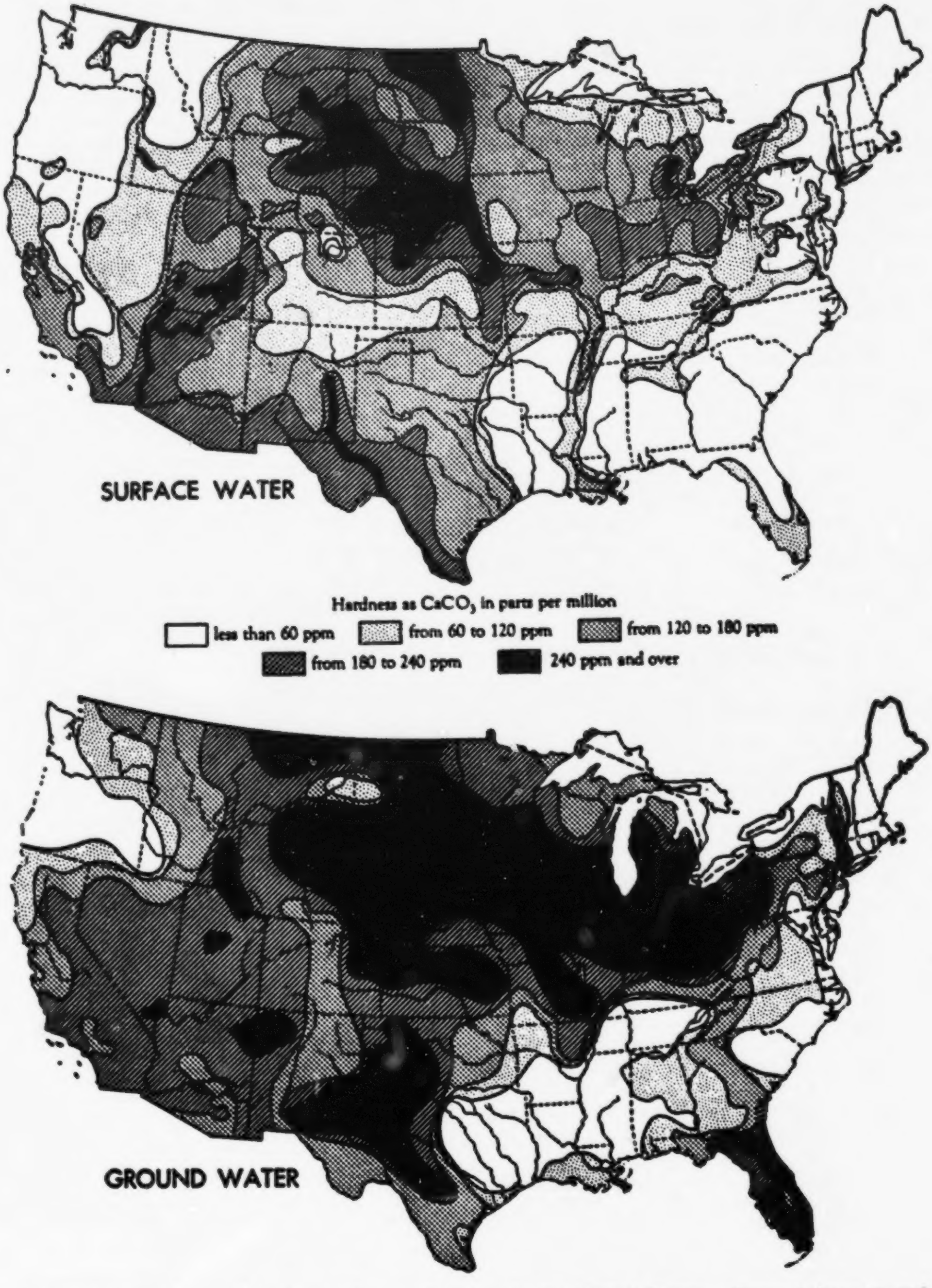
SURFACE WATER
Hardness as $CaCO_3$ in parts per million
less than 60 ppm
from 60 to 120 ppm
from 120 to 180 ppm
from 180 to 240 ppm
240 ppm and over
GROUND WATER

FIGURE M.—Hardness of surface and ground waters in the United States. (From Ackerman and Löf, *op. cit.*, page 216.)

OTHER REGIONAL CHARACTERISTICS TO BE CONSIDERED IN WATER DEVELOPMENT

Several other characteristics of the southwestern environment strengthen the conclusion that a pattern of comprehensive water development should be applied to the region. The factors of water quality, elevation above sea level, size of the area, ground-water problems, adaptation of the area to present techniques of weather modification, and periodic soil-moisture deficits for nonirrigation agriculture will be mentioned briefly.

Water quality

The water quality problem of high dissolved solids content was mentioned briefly above. Aside from making many usable waters sensitive to deterioration in reuse, water quality is of interest because there are many millions of acre-feet of ground water in the region which are either of a limited use or unusable because of their dissolved solids content (figs. 6 and M). Both salinity and hardness are very widespread characteristics in the region's surface and ground waters. As is already recognized by the United States in its saline-water program, low-cost desalting can be of great benefit to many parts of the interior of this region as well as to the seacost areas. For the needs of the Southwest alone, research and pilot experiment on desalting should be continued until the technical problems are solved. Research, experiment, and later application of desalting definitely belong in the pattern of comprehensive development for the nine Southwestern States.

Elevation above sea level and size of the area

The distances to be covered in this region may be counted problems for water development both in terms of lateral extent and elevation above sea level. Nearly two-fifths of the land surface of the 48 middle latitude States are included within these 9 States. Even if total regional population reaches 89 million projected in the II-1 series, it still will attain a density of only about 80 per square mile. This is a general measure of the problem of distributing water. Movement of water from districts of surplus to those of deficit will have to contend with distance. In addition, a large part of the total surface of the area is at relatively high elevations above surplus water sources which may be considered as supplies.

Well over one half of the total area of the nine-State region has an elevation in excess of 1,000 feet above sea level, and much of the area from central Texas, west central Oklahoma, and central Kansas west to the Sierra Nevada Range in California varies between 2,000 and 7,000 feet above sea level. Water yield per square mile is relatively low throughout most of the area between 1,000 and 7,000 feet. The major zones of precipitation and consequent water generation are peripheral to these elevated plains and plateaus. Aside from California, two major zones may be distinguished: first, the comparatively low Texas Gulf coastal plain together with the low plains in northeastern Texas, eastern Oklahoma, and eastern Kansas; and secondly, the southern Rocky Mountains, which rise above the prevailing levels of the water-deficit lands.

TABLE H. *A model of long-distance water transportation by conduit in Western United States*

A. Physical dimensions:	
1. Distance from intake to point of delivery, miles	100
2. Total lift (4 steps), feet	400
3. Conduit diameter (internal), feet	9
B. Conduit construction and maintenance:	
1. Type of conduit: lock joint steel pipe embedded in prestressed concrete	
2. Conduit construction costs, per mile [1]	$850, 000
3. Total conduit construction costs	$85, 000, 000
4. Annual operation and maintenance costs	$425, 000
C. Pumping facilities:	
1. Number of stations	4
2. Individual pumping station capacity, cubic feet per second	465
3. Amount of water lifted annually, acre-feet	260, 000
4. Total construction and equipment costs, 4 stations [2]	$4, 296, 000
D. Miscellaneous investment costs [3]	$2, 000, 000
F. Total project investment costs	$91, 296, 000
F. Electric power and pumping costs:	
1. Annual power requirements per plant, kilowatt-hours	30, 160, 000
2. Power requirements per pumping plant per acre-foot, kilowatt-hours	116
3. Total power requirements per acre-foot, kilowatt-hours	464
4. Assumed power costs per kilowatt-hour, mills	5
5. Pumping costs per plant per acre-foot	$0. 58
6. Pumping costs per acre-foot for 100 miles	$2. 32
7. Total annual power costs	$603, 200
8. Annual operating and maintenance costs, except power, 4 stations	$400, 000
G. Financing:	
1. Taxes	0
2. Annual interest charges at 4 percent	$3, 651, 000
3. Annual sinking fund charges for conduit and other construction costs (50 years)	$1, 740, 000
4. Annual amortization charges for pumping plant and equipment costs (30 years)	$143, 200
5. Total annual amortization charges	$1, 883, 200
H. Cost summary:	
1. Total annual fixed and operating costs for the 100-mile line	$6, 962, 400
2. Annual costs per acre-foot	$26. 77
3. Costs of transporting 1,000 gallons of water 100 miles	$0. 08

[1] Includes site preparation, transportation of conduit sections to emplacement points, and backfilling.

[2] Assumes a static head of 100 feet, and a working head of 110 feet.

[3] Includes easement and costs of transmission lead-ins.

Runoff stored on the coastal plain of Texas or on the lowlands east of the margin of the Great Plains could only be made available to the southern Great Plains at the expense of a lift of hundreds or even thousands of feet. Thus water impounded at the 300 foot contour on the Brazos River, for example, and transported to the Lubbock area of Texas would require a lift of about 3,000 feet

On the west side of the Rocky Mountains, water collected by the Colorado River system issues from the mountains in deeply incised valleys and canyons. Thus use of water in Utah, Nevada, and Arizona would generally require considerable lifting. The situation is particularly difficult in Arizona. While the major areas of potential water use in southern Arizona are comparatively low, some 400 to 2,600 feet above sea level, generally below the level of the Colorado River at the point where it enters the State, the high southwestern lobe of the Colorado Plateau intervenes between the middle Colorado River and the major centers of population.

Sources of selected cost estimates

Pumping plant construction and equipment cost estimates are based on schedules of plant and equipment costs per unit of capacity and working head in: U.S. Department of the Interior, Bureau of Reclamation, "Estimating Data," Specialist Supplement No. 1 to part 8 "Construction Cost Estimates" of volume X "Design and Construction Reclamation Manual," Tentative Edition, corrected to 1959 price levels on the basis of U.S. Department of the Interior, Bureau of Reclamation, "Construction Cost Trends," Denver, Colo., 1959.

Pumping costs computed from pumping cost data published annually for the Colorado River aqueduct by the Metropolitan Water District (Southern California), although a higher charge per kilowatt-hour was assumed than that prevailing at Parker Dam. Energy requirements per acre-foot of water lifted per unit of vertical distance were derived from Colorado River aqueduct data.

Conduit construction costs were estimated on the basis of per-mile costs for construction of a similar line in Israel as part of the Jordan project, modified for labor cost differentials, construction practices, manufacturing costs, and other costs which might affect total construction costs in the United States. Capacity of conduit is also based on the announced capacity of the Israel line. Source: "Water Planning for Israel, the Central Israel Water Conduit, Preliminary Report," Tel Aviv, October 1959.

The economic meaning of these facts is suggested in table II, which describes in a general way the economic effect of distance and elevation in the movement of water. Water which has moved 400 feet upward over a hundred miles distance, already is becoming high-cost water because of the transportation component alone. The tendency of both distance and elevation thus will be to set some limits upon interbasin water exchanges and enforce dependence upon local supplies. This means that any measure which can reduce the cost of transportation or pumping, and any measure which can bring now unavailable local supplies into use, should be welcomed. Again, the search for and application of such measures is a part of comprehensive development.

Overdraft and other ground water problems

The existence of heavy overdrafts on a number of important aquifers in the region already is so commonly known that it needs no documentation here. They may cause an increase in lifting distance, or salt water intrusion into aquifers. These problems already have been faced in some degree by individual States, particularly New Mexico. However, the continued existence of overdrafts of great volume, as on the Texas high plains, and the possible benefit from mining other unexploited aquifers, underline the need for an approach which integrates ground and surface water use and coordinates their development so as to assure an efficient matching of supplies and requirements within this century. Planning for the use of surface waters in this region without simultaneous consideration of and planning for the use of ground water is only a half measure, and should be so branded. Thus the need for another element of comprehensive development is added.

Adaptation of the region to present techniques of weather modification

With all of their climatic and terrain handicaps, the southwestern nine States are favored in being one of the two sections of the country where the known methods of weather modification can be applied with some promise of results. The frequent occurrence of mountain ranges throughout the western two-thirds of the region gives it a major part of the terrain suited to the artificial modification of orographic rainfall. Although the author has noted elsewhere in this report the prevailing scientific opinion on the great need for fundamental meteorological study in this subject, continued experiment within the region and preparation for the application of weather modification as a coordinated part of water supply techniques are warranted not only by the future water requirements of the region, but also by its special geographical environment.

Problems of soil water deficit in low rainfall periods

In spite of the importance of irrigation to the Southwest it must be remembered that there are hundreds of thousands of square miles, particularly in the eastern half of the region, where agricultural land use is dependent upon soil moisture. Such land use is most susceptible to the hazards of drought. Although water storage can mitigate some hardships when the extended drought periods come, such storage does not show promise of influencing the welfare of more than a minor proportion of the dry farming and grazing areas of these States. More effective answers are likely to come only when the secrets of the rainfall cycle are unraveled to the point where projections can be made with some degree of certainty for rainfall receipts. This is a part of the effort which should be encouraged and supported in prognostic hydrology. Another important reason for the support of prognostic hydrology lies in the provision of basic data for planning stream regulation. However, the added reason found in the need for accurate determination of the moisture cycle makes prognostic hydrology an outstandingly important element in the group of comprehensive development techniques.

A SKETCH OF COMPREHENSIVE DEVELOPMENT AS AN APPROACH FOR THE SOUTHWESTERN NINE STATES

It has been suggested in the text of this report (sec. VII) that a technical study commission should recommend for the evolution—technically, scientifically, and administratively—of a pattern of comprehensive development of water resources in the nine Southwestern States. This is regarded as an essential first step in evaluating the potentialities of comprehensive development, should a policy of examining this approach be elected by the Congress. Nevertheless, it may be helpful to sketch in a general manner a possible comprehensive development approach in the Southwestern States.

In the following discussion, joint Federal-State action in planning is assumed throughout. Reference will be made only to public action, because this is the policy issue under consideration. At the same time, it is realized that private entrepreneurship does have an important place. There is no intention of minimizing the responsibilities of private organization by their omission in this description.

One principle observed throughout the approach is that a desirable system of water development not only balances and meets efficiently the requirements of all purposes currently, but also prepares well in advance for meeting anticipated future requirements, giving due consideration to the application of new technology.

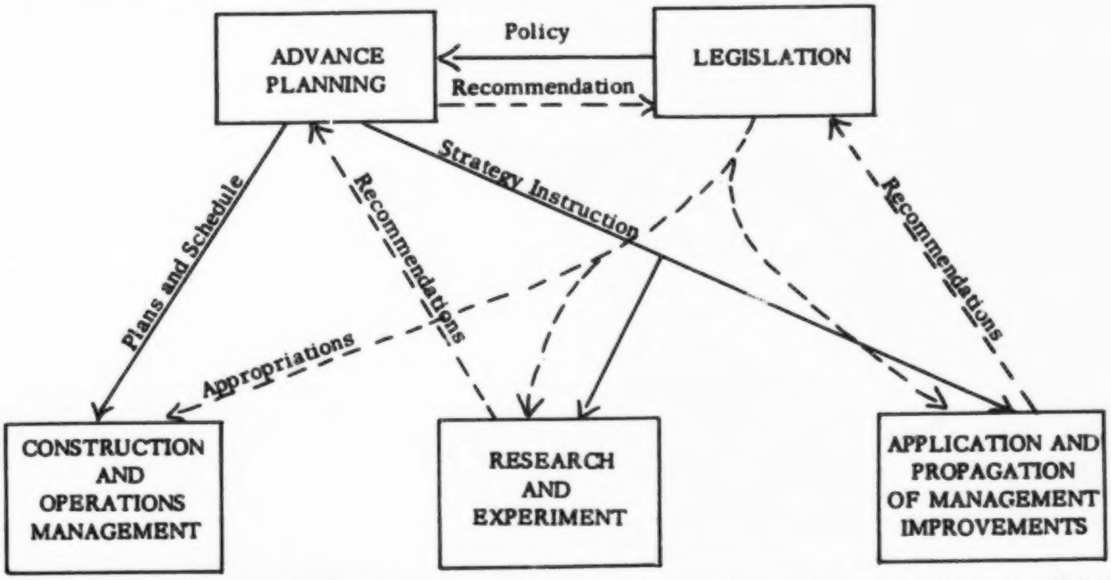

FIGURE N.—Some functions in the implementation of comprehensive development, as related to each other and to legislation.

The implementation of comprehensive development may be described under four general functions: advance planning, construction and operations management, research and experiment, and the application and propagation of management improvements. Their general relationship is shown in Figure N, along with their relation to the function of legislation. A very important function, at least in the initial stages of establishing a pattern of comprehensive development, is that of advance planning. In this step not only would the alternative methods of meeting expected requirements be anticipated, but the strategy of research and experiment and the application of appropriate management improvements would be determined. Recommendations would be received from research and experiment and evaluated in their possible application to action programs. The possible activities which might be undertaken within these four functions are outlined below. The functions alone are discussed without reference to agency or administrative organization.

Advance planning

(1) The beginning of advance planning for comprehensive development, and indeed the logical beginning for any future water development in the Southwest, would be the construction of water consumption models by State. The responsibility for producing these models probably should be that of the individual States, undertaken with appropriate technical guidance and consultation by the Federal Government. The objective would be one of projecting the consumption pattern in its variations over time and space within the State, and arriving at estimates of requirements by periods. Consideration of the entire four decades up to the year 2000 does not seem unreasonable.

(2) The second step under advance planning would be the application of prognostic hydrology to a determination of the available supply. The objective, insofar as technical capacities permit at any given time, would be that of projecting the availability of water within the State, and

by geographic sections, in its variation over time. The "bank account" of ground water would be considered, among other things. At least at the outset, primary responsibility for this function might well reside with the Federal Government, although the active cooperation of State agencies will be important.

(3) The third step would be an application of operations analysis to the appraisal of alternatives of matching supply and demand, including stream regulation, demand engineering techniques, and other methods. Operations research can be applied to comprehensive development in its entirety as well as to the integrated multiple-purpose development alone.

(4) It is certain that regulation of surface flow will turn out to be one of the important means for meeting requirements. A fourth step therefore will be the design of future increments to the storage and regulation system, including the application of operations analysis techniques to that design. Advantage will be taken of system operation on a basin or interbasin pattern so as to harvest as many benefits as possible from scale economies.

(5) In the light of the above appraisals and with the aid of pertinent additional data, strategies would be developed for the conduct of research and experiment, and the application and propagation of management improvements. In the light of these appraisals and other pertinent data, instructions would be issued for such strategy, or recommendations for legislative action made.

(6) As under present practices, plans and a schedule for construction of needed regulation facilities would be recommended for periods of the length determined as reasonable by the legislative bodies making appropriations.

Construction and operations function

A brief description of this function will suffice because it is an established activity, the outlines of which are well known. Detailed planning of projects designated for construction, and the actual construction of reservoirs, canals, conduits, and other means of transporting water, navigation channels, and other needed facilities fall under it. Operation and maintenance of all regulation works, facilities producing vendible services, and other operational surveillance are included. One activity which probably should be added as routine is the monitoring of water quality.

Research and experiment

The vital importance of the research and experiment function to the realization and application of technical capacities in the future cannot be overstressed. The range of appropriate attention within this function is wide. It includes such subjects as the development of systems analysis methods for planning, the techniques of prognostic hydrology, water conserving agronomy, the application of weather modification, ground water exploration and appraisal, desalting, lessening the cost of transporting water, evaporation-suppression storage techniques, and still other subjects. Research on some, of course, is being carried on at the present time. The difference which comprehensive development will bring comes not only in added emphasis on techniques which publicly receive lesser attention now, but in an effort to attack future water supply problems on a broad front with a balanced strategy. It does not mean the centralization of water research in one or a few agencies, but rather the continuance of present research functions with the guidance of a coordinated view of potentialities and needs for research and experiment. Recommendations flowing from this function to advance planning can be one of the best assurances of future efficiency in development.

Application and propagation of management improvements

The construction and operations function is one important means of realizing development which has been planned and designed. It will continue to be so under a pattern of comprehensive development. At the same time, it is equally important to recognize a final function, that of applying and propagating management improvements. Where there are several alternatives, each of which can contribute a significant increment to the final efficiency of development, and where many entrepreneurs, both public and private, are responsible for final action, it is an unavoidable function. Its recognition will be especially important in a technological environment where improvements are proceeding at the rapid rate we expect them to. Included within this function would be all activities related to the application of "demand engineering," including recycling techniques, agronomic water conservation, and planned location of demand. The establishment of standards of efficient consumption, within a given use, the application of use priorities, and the integration of ground and surface water management also come under this function. Action would be taken through publication, public information programs, consultation with administrators, preparation of recommendations for legislation, and in other ways.

NEED FOR FURTHER STUDY

This sketch is not intended as a pattern for the application of comprehensive development to the Southwest without further study. It is instead an informational model for use in deciding whether or not further examination of comprehensive development should be a part of immediate Federal policy. Nonetheless it is the author's belief that an approach incorporating the idea of comprehensive development can help the Southwest to provide the maximum opportunity for income growth, optimum opportunities for settlement, and opportunity for agricultural expansion.

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